TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 876

THE LIMITING USEFUL DEFLECTIONS OF CORRUGATED METAL DIAPHRAGMS

By W. A. Wildhack and V. H. Goerke
National Bureau of Standards

Washington
December 1942

1W

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 876

THE LIMITING USEFUL DEFLECTIONS OF CORRUGATED METAL DIAPHRAGMS

By W. A. Wildhack and V. H. Goerke

SUMMARY

The limiting useful deflection of a diaphragm may be defined as that deflection which is followed by an arbitrarily chosen allowable limit of hysteresis, aftereffect, drift, or zero shift. Preliminary results reported previously indicated that the limiting deflection is mainly dependent on the diameter, and the material, and only slightly dependent on the thickness of the diaphragm.

In order to investigate further the useful limits of diaphragm performance, measurements have been made on a large number of corrugated diaphragms of similar shapes but of various sizes and various metals. The materials studied include phosphor bronze, beryllium copper, A-Nickel, B-Monel, K-Monel, and Inconel. The apparatus used in making the measurements is described.

Data were obtained on the relations between pressure and deflection, deflection and hysteresis, time and drift under constant load, time and recovery after release of load, and zero shift and deflection for the various diaphragms. Many of the results are presented graphically. The performances of the different materials are compared and the characteristic constants for each material are deduced for use with design formulas.

The results are analyzed to determine the correlation of the limiting deflections with the thicknesses and diameters of the diaphragms and the elastic properties of the materials used.

INTRODUCTION

Metal diaphragms are useful in measurement of pressures because of their ability to give definite deflections as a function of the applied pressure. They fall short of perfection because their strength decreases with increasing sensitivity and because metals show deviations from ideal elastic behavior, hereinafter referred to as "elastic defects," such as drift, hysteresis, aftereffect, and zero shift.

Because of their numerous applications in aircraft pressure-measuring instruments, the National Advisory Committee for Aeronautics has financially supported an investigation at the National Bureau of Standards on the properties and design of corrugated diaphragms.

It is apparent that, other things being equal, the diaphragm most generally useful is the one with the greatest sensitivity, that is, the greatest ratio of deflection to load. For a given thickness and diameter, flat diaphragms are initially more sensitive (that is, the ratio of deflection to slight applied pressures is greater) than corrugated diaphragms. Corrugated diaphragms are, however, almost universally used in pressure-measuring instruments because their average sensitivity over a large range of pressure is greater than that of flat diaphragms of the same size, their zero-position under no load is more stable, and a rather wide range of pressure-deflection relations may be obtained for a given size of diaphragm by using different depths or shapes of corrugation. In general, the corrugated diaphragms can stand much larger deflections without permanent deformation.

The theory of circular flat diaphragms, both with clamped and with free edges, has been developed with some success (references 1 to 7). An approximate formula indicating the general effects of change of corrugation outline has recently been derived (reference 8) but it has not been possible to evolve satisfactory theoretical design formulas for corrugated diaphragms.

In the first phase of the investigation at this Bureau, the results of which have been published in reference 9, generalized design formulas were derived by dimensional analysis of experimental data obtained from a series of dimensionally similar diaphragms. Only one corrugation outline was studied, and deflections were limited to the linear range, 2 or 3 percent of the diameter D. The materials used included beryllium copper, phosphor bronze, and Z-Nickel.

The work reported herein extends the previous work to several other materials and to higher deflections and correlates the limiting useful deflections of diaphragms of the various materials with the elastic defects observed, with the elastic constants of the materials, and with the thicknesses and diameters of the diaphragms.

FACTORS AFFECTING PERFORMANCE OF DIAPHRAGMS

Similar diaphragms made of different materials differ in stiffness, as would be expected because of the different elastic moduli, and also in the deflection which they will stand without permanent deformation. The performance of a diaphragm is determined by both geometrical and mechanical factors, such as size, shape, and method of holding the edges, and by the intrinsic elastic properties of the materials of which it is made.

It is logical as well as convenient to separate, as much as possible, the effects of variation of the mechanical factors from those due to variation of elastic properties from one material to another. In this investigation, the mechanical factors of unknown effect were held fairly constant by using only one shape (the different sizes were dimensionally similar) and by always clamping the edges in the same manner. The thickness and the diameter are, of course, geometrical variables; their gross effects on stiffness have already been studied in part. The previous study was limited mainly to deflections of less than 2 or 3 percent of the diameter. Over this range, the pressure-deflection relationship is very nearly linear (within 1 or 2 percent) for this shape. Data have now been obtained on the pressure-deflection characteristics up to the maximum useful deflections, which for some diaphragms is nearly 8 percent of the diameter. Knowledge of the characteristics of one diaphragm shape was thus extended. This knowledge is of some value *per se* and may be helpful when it is possible to compare the characteristics of diaphragms of several shapes and thus obtain more general design formulas.

The maximum useful, or "limiting," deflection of a diaphragm is a somewhat indefinite quantity. For instance, a diaphragm may continue to deflect slowly under a constant load to an undesirable extent or fail to return immediately to its zero position upon release of load, even though it may regain its original position after a sufficiently long time. For this reason, no single value is to be taken as the limiting deflection of a diaphragm for all purposes. The useful limits are to be defined in terms of the elastic defects which become apparent under increasing loads. These elastic defects include:

1. Hysteresis - the difference between the deflections of the diaphragm at a given load, for decreasing and for increasing loads

2. Drift - the increase of deflection with time under a constant load

3. Aftereffect - the deflection remaining immediately after removal of the load, that is, hysteresis at no load

4. Recovery - the decrease of aftereffect with time under no load. (The term may also be applied to the time decrease of hysteresis at a constant load but was not studied in this sense.)

5. Zero shift - the permanent deformation, that is, the difference in zero position before loading and sufficiently long after unloading for recovery to occur; or the difference between aftereffect and recovery

Zero shift appears to be a fairly absolute measure of useful deflection, that is, if each loading causes permanent deformation, it is apparent that the loadings cannot be repeated indefinitely. Even this criterion is, however, to be closely scrutinized. Many diaphragms will show some zero shift after each of the first loadings. Afterward their performance (up to that load) becomes stabilized and they are said to be seasoned. It is characteristic that imposition of a higher load will again cause a zero shift, which will decrease with succeeding loadings and stability may again be obtained. Heat treatment for stress relief will often reduce the number of workings necessary to attain stability. There finally comes a point, however, at which the total deformation incident to the working is so great that the characteristics of the diaphragm over the low-pressure range are entirely different from the original. Alternatively, the diaphragm may break during seasoning before stability is attained.

As a practical definition, the useful limit may be considered to lie in the range where the elastic defects begin to increase sharply with increasing deflection. The determination of the course of these defects as functions of deflection, time, number of workings, heat treatment, and material involves an almost impossible amount of testing. The results obtained are therefore indicative rather than comprehensive, qualitative rather than quantitative, and comparative rather than exact.

In many cases the useful limit may be only indirectly related to the limiting factors previously mentioned. It may be more important to use only that part of the range in which the pressure-deflection characteristic, or some other relation, is best suited to the particular application. It is the intent of this paper to present data in tables and in curves that will enable the user to determine the practical limits for a particular purpose.

MATERIALS

A list of possible materials for diaphragms would be quite extensive, since the varying conditions of their use will include as desirable properties many other factors besides elastic behavior. Slack diaphragms of fabric or rubber have long been used to attain an approach to zero stiffness. Fiber or paper diaphragms serve for sonic purposes. Quartz, glass, and plastics are possible materials for elastic diaphragms although unknown as yet in practice. Metal diaphragms are, of course, used in pressure-responsive devices for many applications, from sensitive barometric variometers which respond to a whisper to high-range indicators of explosion pressures. The choice of metal is often governed by chemical properties (especially corrosion resistance), finish, appearance, and by price, as much as by the mechanical or elastic properties. In the final design, the more data there are available on mechanical and elastic properties, the better the choice that can be made. The metals of which diaphragms are most commonly made are phosphor bronze, beryllium-copper alloys, nickel, nickel alloys, and steel. Aluminum alloys have not had much application in this field. The diaphragms are usually stamped or pressed, rarely spun, from sheet stock of uniform thickness.

In the present investigation, tests have been made on diaphragms of phosphor bronze, beryllium copper, A-Nickel, and the nickel alloys B-Monel, K-Monel, and Inconel.

Chemical analyses were made of some of the materials. The compositions are given in table I. Complete analyses were not made on the nickel alloys; therefore, only nominal compositions for these alloys are listed.

Hardness measurements were made with a Knoop indenter (reference 10) on many of the materials before and after the working incident to formation and after heat treatment, if any. The indentations were made on the top of the diaphragm corrugations after the material had been sufficiently polished to remove most of the oxide coat. In general, there was no significant variation from one corrugation to another. The Knoop indentation numbers are very roughly equivalent to Brinell numbers that might be obtained on thicker specimens of the same materials. The results are given in table II.

The hardness of the various materials is of importance as an indication of the attainment of the optimum physical properties. For maximum deflection a diaphragm of a given material should be so formed and stress-relieved that the diaphragm has the maximum possible hardness.

Phosphor Bronze

The phosphor bronze was obtained in strips 3 to 6 inches wide and of nominal thicknesses 0.002, 0.003, 0.004, 0.006, and 0.008 inch. The percentage of the various constituents of the alloy as determined by chamical analysis is included in table I.

Heat treatment.- The material as received had been hardened by cold rolling and was found to be too hard to form satisfactorily in the dies used. In order to soften the material, the procedure followed in previous work (reference 9) was first used. This procedure consisted in heating the diaphragm blanks, packed in carbon, for 1 hour at 425° C. After this treatment, the material could be satisfactorily formed. The elastic properties of the diaphragms were found to be poor. The same period of heating at 390° C necessitated formation in two stages, but performance was somewhat improved. A heat treatment described by Harrington and Thompson in reference 11 was then tried, although the treatment had been developed for a phosphor bronze of somewhat different composition. The blanks were heated in carbon as before but at 250° C for 100 hours. The diaphragms could then be formed, although with some difficulty.

The performance of diaphragms made of the material annealed at 425° C could be stabilized at 2 percent D (center deflection = 2 percent of diam.) by considerable working or by heat treating at 300° C for 1 hour followed by several loadings. With the 100-hour, 250° C treatment before forming, some improvement in the elastic properties was apparent. After considerable working, stability could be attained up to about 4 percent D. If a further heat treatment of 50 hours at 250° C following formation was given, the performance could be stabilized by moderate working for deflections up to 5 percent D.

Although the heat treatment applied was possibly not the best possible for the phosphor bronze used in this investigation, special studies of heat treatment are beyond the scope of this work.

Hardness.- Hardness measurements were made on samples of the sheet stock, on diaphragm blanks that had been given the preliminary heat treatment (1 hr at 425° C, or 100 hr at 250° C), on formed diaphragms, and on diaphragms after the stress-relief treatment (50 hr at 250° C). The results are given in table II.

The heat treatment at 425° C reduced the Knoop indentation number to about half its original value, while the 250° C heat treatment decreased the Knoop indentation number by less than 20 percent in most cases. Formation of diaphragms of phosphor bronze that had been heat-treated 100 hours at 250° C increased the hardness to a little below its initial hardness. Other materials show an increase of indentation number incident to formation up to more than double that of the blank. The stress-relief treatment (50 hr at 250° C) reduced the hardness to about the same value as before the forming.

It is apparent that the 100-hour, 250° C heat treatment relieved the stresses with much less reduction in hardness than did the 1-hour, 425° C treatment.

Beryllium Copper

The beryllium copper was obtained in strip form 3 to 6 inches wide and in thicknesses of 0.002, 0.003, 0.004, 0.005, and 0.008 inch. A few disks $1\frac{3}{4}$ inches in diameter and 0.013 inch thick were also obtained. Only dead-soft material was used, since material hardened by rolling could not be easily formed to the shape of the dies. The composition as determined by chemical analysis is included in table I.

Heat treatment.- After the diaphragms were formed, they were heated for 1 hour at 300° C. This treatment gives good results, but more recent advice from the Beryllium Corporation based on work with springs suggests that a higher temperature would perhaps be better for reducing the drift under load. Results of tests of a few diaphragms of a different alloy (Berylco No. 25, described in reference 12), which were heated for 2 hours at 330° C, are included in this report.

The diaphragms in this investigation were heated in air without clamping. The discoloration due to the formation of a thin black oxide film during heating could be easily removed by hydrochloric acid without apparent change in the performance of the diaphragms.

Hardness.- Measurements were made on samples of the soft sheet stock as received after heat treatment, and on the diaphragms after heat treatment. The results are listed in table II.

The heat treatment increased the Knoop hardness number from 125 to about 335. The very small difference of hardness between the heat-treated sheet stock and the heat-treated diaphragms indicates that the working incident to formation had little effect on the final hardness of the formed diaphragms.

Precipitation-hardenable alloys, such as beryllium copper, have the advantage that the diaphragms can be formed from the relatively soft material; whereas materials that depend for their final hardness on the hardness of the blank and the work hardening incident to formation must be formed from blanks of the maximum permissible hardness.

Nickel and Nickel Alloys

The nickel and the nickel alloys were supplied through the courtesy of The International Nickel Company, Inc. which also heat-treated the diaphragms made of K-Monel. Four materials were supplied: A-Nickel, B-Monel, K-Monel, and Inconel. The materials were of one thickness, 0.006 inch, and were supplied in annealed soft and in the rolled quarter-hard conditions. Data on chemical composition are included in table I.

Heat treatment.- Most of the diaphragms of A-Nickel and B-Monel were given a stress-relief treatment after formation. This treatment consisted in heating the diaphragms in carbon at 330° C for 1 hour. Inconel was given a stress-relief treatment at 425° C. A few of the diaphragms that had not been given the stress-relief treatment were also tested.

After being formed, the diaphragms of K-Monel were heat-treated by the International Nickel Company for 16 hours at 580° C. (See reference 13.)

Hardness.- Measurements similar to those on the other materials were made on all of the nickel alloys. The data are recorded in table II.

The Knoop indentation number for A-Nickel was raised from 80 to 170 during the process of formation and stress relief. The Knoop indentation numbers for these diaphragms were considerably higher than for the quarter-hard sheet stock (Knoop indentation number 148). This increase in hardness indicates that the hardening incident to formation was more than equivalent to that obtained by rolling quarter-hard. Diaphragms could not be formed of the quarter-hard material because rupture occurred in the early stages of formation.

The stress-relieved B-Monel diaphragms formed from the soft material had a Knoop indentation number of 200, the soft stock, a Knoop indentation number of 102. Diaphragms could not be successfully formed from the quarter-hard stock B-Monel with a Knoop indentation number of 222.

Diaphragms of K-Monel were successfully formed of the soft material and, by the use of light clamping forces, of the quarter-hard material. The Knoop indentation number of the soft K-Monel was increased from 192 to

273 during formation, and to 324 by the precipitation hardening. Similarly, the indentation number of the quarter-hard material was increased from 215 to 335. The final hardness of the K-Monel diaphragms was about equal to that of the beryllium copper.

The strip Inconel was the hardest of the nickel alloys, with a Knoop indentation number of 248 for the soft material. After formation and stress relief, it was about as hard as K-Monel or beryllium copper.

MANUFACTURE OF THE DIAPHRAGMS

The diaphragms used in making these tests were made by the method of hydraulic pressing. Dies of four sizes were used, all having dimensionally similar shapes, as shown in figures 1 and 2. The depth of all of the corrugations was 0.0167D, except the outer offsetting corrugation, which was a 120° arc of radius D/16. The effective diameters D of the diaphragms formed with these dies were $1\frac{1}{2}$, 2, $2\frac{1}{2}$, and 3 inches. The rim width was one-fourth inch for all sizes. The outside diameter was the same for all the dies; they could, therefore, be used interchangeably with the same base.

The apparatus used for making the diaphragms included a hand-operated hydraulic press of 18 tons capacity; a hydraulic pump, also hand operated; the dies; a base for the die; paper gaskets; dental dam; and circular metal blanks. The press was used to clamp the die and its base and was also used in the course of testing the diaphragms. Figure 3 is a photograph of the press with the testing apparatus. When the press was used for making the diaphragms, the micrometer tip A, seen projecting below the upper platen in figure 3, could be screwed out of the way. The hydraulic pump was connected by 1/8-inch copper tubing to the base 5 (fig. 2). In operation, the clamping force was made greater than the hydraulic force exerted by the pump in forming the diaphragm. The difference between these two forces was the effective clamping force.

The die rested in its base with the blank between them. Paper gaskets were necessary to prevent leakage between the blank and the base at high forming pressures. The pressure fluid was conducted to the lower side of the blank through the hole in the die base shown in figure 1.

Annular rings (1/32 in. thick) were laid in the base to center the blank and the gasket. The die was automatically centered by the cylindrical projecting rim of the base. Each die had vent holes (see figs. 1 and 2) to allow the air between the blank and the die to escape.

In the formation of some of the diaphragms, the procedure was as follows: The paper gasket and the blank were placed on the pressure base. The die was placed on top. The die and the pressure base were placed together in the press and clamped with a force sufficient to clamp the edge of the diaphragm with a pressure up to 10,000 pounds per square inch in the presence of the hydraulic pressures (up to 9500 lb per sq in.), which were then applied. After the pressures were released, the formed diaphragm was removed.

A few of the diaphragms were made with a thin rubber sheet (dental dam, 0.012 in. thick) between the blank and the die; these diaphragms had characteristics different from those of the fully formed diaphragms. Most of the fully formed diaphragms were made in two stages: first the rubber backing was used and then the forming was completed without the backing. This method gave a more uniform thickness for the various corrugations. By this "two-stage" method, diaphragms could also be made of harder or thinner materials than could be directly formed in one stage. The thickness of diaphragms formed by this method was usually 8 to 10 percent less than that of the blanks.

Another technique found useful in forming harder materials was the use of clamping forces small enough to permit the edges of the blank to be pulled in and leave a narrower rim. In order to avoid too great dissymetry, the diaphragm was partly formed (with about one-third the full forming pressure), the die was removed, and the partly formed diaphragm was rotated 180°. The forming operations were then completed. This technique minimized the uneven pulling of the edges due to slight unevenness of the gasket, the die, or the die base.

After heat treatment, some of the diaphragms were equipped with reinforcing disks as a part of the regular manufacturing process. The disks were of copper or phosphor bronze 0.03 inch thick or nickel 0.015 inch thick. After heat treatment of the diaphragms, the disks were soldered on in the center of the convex side. Their diameters were $D/4$, the same as that of the uncorrugated central area.

The purpose of the disks was to stabilize the central part and to make the construction correspond to the practical case in which an indicating mechanism, contacts, or mounting connections are fastened to the center of the diaphragm.

The zero shift of reinforced diaphragms was in some cases somewhat larger than that of similar diaphragms without reinforcing disks. This defect was possibly due to faulty soldering. Cadmium-zinc solder (melting point = 260° C) with zinc-chloride flux seemed to give less erratic results than 50-50 lead-tin solder. Disks were, however, omitted for most of the hysteresis and drift tests to avoid effects extraneous to the diaphragms themselves.

Inasmuch as the four different sizes were dimensionally similar and the main effects of variation of diameter on the load-deflection characteristics of diaphragms of this shape had been determined in reference 9, not all of the sizes were made in all materials for this study.

METHODS OF TESTING

The rims of the diaphragms were clamped by a hydraulic press for testing. The testing apparatus may be seen in figure 3. The steel pressure chamber B has four annular steps to fit the four different diameters. Steel cylinders (such as C) of 1/4-inch wall thickness, which is the width of the rims of the diaphragms, were constructed with inside diameters equal to the diameters D of the corrugated part of the diaphragms in order to clamp the edges.

The diaphragm was placed on a greased paper gasket on the annular step in the pressure chamber. The cylinder C (fig. 3) was seated on the rim of the diaphragm, and the assembly was centered on the lower platen of the press. When the hydraulic pressure was applied to raise the lower platen, the cylinder clamped the diaphragm directly under the micrometer A mounted in a hole through the upper platen. The clamping force (about 5 tons) could be maintained by a hand pump and a pressure gage to the constancy required to keep errors due to variation of clamping force to less than the sensitivity of the micrometer.

Air pressure measured by water or mercury manometers M could be applied to the diaphragm by means of a hand-operated air pump. For many tests it was not convenient to wait for pressure and temperature equilibrium to be reestablished after change of air pressure. A hydraulic method of loading was therefore adopted for much of the work. The space in the pressure chamber B below the diaphragm was filled with water. A metal tube connects the pressure base through stopcocks C_1, C_2, C_3, C_4 shown in figure 4 to water and mercury columns W and M. These manometers are in parallel, the ranges being 140 centimeters of water and 210 centimeters of mercury, respectively.

Pressure could be gradually varied by raising or lowering the reservoirs R_1 or R_2, or it could be rapidly changed by adjusting the pressure in either manometer with the stopcocks C_1 and C_3 closed and then opening the appropriate stopcock. The stopcocks were opened slowly enough to prevent overpressure due to surging. The effective pressure on the diaphragm was not exactly that indicated by the manometer before opening the stopcock, because the deflection of the diaphragm would cause a change in the lower mercury level. A correction for this change was made by reading the positions of both the upper and the lower meniscus (when mercury was used) and allowing for the change in height of the column of water between the lower meniscus and the diaphragm.

The accuracy of the pressure measurements was better than 0.5 millimeter on the manometers. The micrometer, held by an insulating bakelite bushing in the upper platen, was connected to a graduated wheel E, 12.5 inches in diameter, the rim of which was ruled with 500 divisions. The micrometer screw had 40 threads to the inch; each division or unit on the wheel therefore corresponded to a movement of 5×10^{-5} inches. Readings were estimated to tenths of a wheel unit and could be repeated with about this precision. The accuracy of measurement is, of course, not so great as the sensitivity indicated but, for measurements of drift or aftereffect, the sensitivity of the measuring apparatus is more important than the absolute accuracy. An electric circuit was so arranged that, when the micrometer tip touched the diaphragm, current flowed in a galvanometer and moved a spot of light reflected from the galvanometer mirror. Contact could thus be visually determined. A voltage of only $1\frac{1}{2}$ volts was used, and the current was limited by a 0.5 megohm resistance to avoid sparking. The micrometer was fitted with a small rounded tip of steel. The surface of the diaphragm or reinforcing disk was cleaned and polished over the central area where the micrometer tip touched.

The pressure chamber was so designed that the diaphragm could be tested with either side up. Since the outline is not symmetrical about the plane of the rim, the load-deflection characteristics would be expected to be different in the two directions. A few of the diaphragms were tested in both directions but most of them were tested with the pressure applied to only the convex side.

Although the temperature was not closely controlled and tests were made throughout the range of room temperatures from 20° to 30° C, the temperature variation during any one test was seldom as much as 1°.

Pressure-Deflection Tests

The relationship between pressure and deflection for the various sizes, thicknesses, and kinds of diaphragms was not the main object of this investigation, the laws relating these variables having been determined in the earlier study (reference 9). In order to study the elastic defects it is necessary to deflect the diaphragms, and data on their pressure-deflection characteristics must be obtained. New materials were being investigated, and the old ones were being used to larger deflections than in the earlier work. A comparative study of the pressure-deflection characteristics is, therefore, of considerable interest.

When pressure-deflection data was obtained, the zero reading was first taken with no pressure applied. The micrometer was then screwed up, a small pressure was applied, and the micrometer was screwed down to make contact. The process was repeated for successively higher pressures. At each pressure the position of the micrometer wheel was noted for successive contacts made 10 to 20 seconds apart; and the reading was recorded when two successive contacts occurred twice at the same wheel position, that is, within 0.1 wheel unit (5×10^{-6} in.), which was found to be a good indication that further short-time drift would be negligible. From 1 to 3 minutes were usually required at each pressure.

The stepwise method of loading is similar to the most general conditions of usage of diaphragms. The deflections obtained in this manner for a given pressure are presumably equivalent to those that would be obtained some time after sudden applications of the same total pressure.

Hysteresis Measurements

The diaphragms were loaded in the stepwise manner to a given maximum deflection and were held at this pressure for at least one-half hour. The pressure was then reduced stepwise and readings of deflections were taken for each pressure. Time was allowed at each step for short time drift to disappear, that is, measurements were recorded within a few minutes after the pressure was obtained but only when successive readings 10 to 20 seconds apart agreed within 5×10^{-6} inch. This procedure required 1 to 3 minutes. The entire procedure was repeated for each of a number of different maximum deflections.

The hysteresis was defined as the difference between the deflections for decreasing and for increasing loads. When a permanent deformation occurred for large loads, it was subtracted from the apparent hysteresis, because the deformation presumably occurred at the maximum load.

Drift Measurements

When the diaphragm is slowly loaded, either in steps or continuously, the deflection at any pressure is slightly greater than the deflection obtained immediately after sudden application of the same pressure. Even after slow loading, further drift may occur when the pressure is held constant, but a large part of the drift occurs simultaneously with the slow loading and is not apparent as such. Most pressure-measuring instruments are used with slow loading or its equivalent. Calibrations are normally made for this condition, usually by stepwise loading and waiting a short time at each load, just as was done in obtaining the load-deflection characteristics of the diaphragm. Drift that occurs beyond this amount is sometimes called long-time drift. The long-time drift differs from the short-time drift mainly in magnitude. Of course, if the diaphragm is overstressed, continuing deformation is to be expected. This deformation is referred to as "yielding" and the term "drift" is reserved for recoverable deflections.

For diaphragms under normal use, the long-time drift during a day or more, following the short-time drift that occurs within a few minutes, may be too small to measure conveniently. The investigation of long-time drift is important since in many pressure instruments (for example, altimeters), the diaphragms normally are under maximum load. There was not sufficient time to investigate long-time drift or to determine whether a large value of short-time drift indicates a large value of long-time drift.

For drift tests, sudden loads were applied with the apparatus previously described. The first reading was usually obtained within 10 seconds after the application of load, and further readings were taken as frequently as possible or necessary until equilibrium was apparently established.

Aftereffect, Recovery, and Zero Shift

After any loading test a diaphragm may not immediately return to its original position. For slow unloading or for small loads, the no-load position is usually very near the original position and total recovery occurs within a few minutes. For sudden release of load the aftereffect is larger, and for large loads it may decrease for several days without entirely disappearing. Just when the decrease is assumed to have stopped is somewhat arbitrary, because recovery might be gradual over a long-time period, as for long-time drift. When no measurable change in reading occurred within 1 hour, however, the remaining discrepancy was assumed to be a permanent zero shift.

Measurement of aftereffect was made as part of the hysteresis tests, since the aftereffect is really hysteresis at zero load. Recovery data were also obtained following hysteresis tests to determine whether any permanent zero shift had occurred. In most of such tests, the aftereffect was so small and recovery was so rapid that no significant data on the relation between recovery and time were obtainable. In order to obtain the full measure of aftereffect, measurements were taken following sudden release of load in a manner analogous to that for measuring drift after sudden application of load. Because the micrometer had to be screwed down after the release of the load, through a distance equal to the maximum deflection, the time interval between the change of load and the first reading was somewhat greater than for drift measurements. This interval was usually about 20 to 30 seconds.

RESULTS

Pressure Deflection

In figure 5 are shown several pressure-deflection curves for diaphragms of reinforced beryllium copper. The general course of these curves is typical for diaphragms of this shape, although stiffnesses are naturally different for other materials. Some of these curves extend over a greater range than is usable in practice; the diaphragms began to yield inelastically for deflections greater than 7 to 8 percent of the diameter. Diaphragms of other materials have smaller usable ranges; but, if they could be deflected further without yielding, they would presumably follow somewhat similar curves.

Before it will be possible to compare diaphragms of different materials and of different sizes to determine to what extent the character of the pressure-deflection curve is determined by shape factors, it is necessary to simplify the problem by combining some of the variables.

The method of dimensional analysis as discussed in reference 14 is useful in this connection. It may be applied as follows:

The deflection of a diaphragm is influenced by the pressure applied, the diameter, the thickness, the shape of corrugation outline, and the elastic constants of the material.

Let

X = deflection

D = diameter

t = thickness

P = applied pressure

E = Young's modulus

F = plate modulus $E/(1 - \sigma^2)$

σ = Poisson's ratio

For all diaphragms of the same corrugation shape (dimensionally similar diaphragms)

$$X = f(D,\ t,\ P,\ E,\ \sigma) \tag{1}$$

The dimensionless ratios formed by combinations of the parameters are also related, so that

$$\frac{X}{D} = \phi\left(\frac{t}{D},\ \frac{P}{E},\ \sigma\right) \tag{2}$$

Experimental observations on many diaphragms of the given shape show that the pressure-deflection relation is fairly linear over the range of deflections up to $\frac{X}{D} = 0.02$. For this range of deflections and over the range of $\frac{1000t}{D} = 2$ to 4, the following equation holds for all the diaphragms:

$$\frac{FX}{PD} = 2.25 \times 10^5\ (t/D \times 10^3)^{-1.52} \tag{3}$$

The absolute magnitude of the exponent increases beyond each end of this range of $\frac{1000t}{D}$.

The general curve developed as figure 9 in reference 9 for diaphragms of this shape over the range of X/D up to 0.02 is reproduced as figure 6. The data plotted were determined from data for reinforced beryllium-copper diaphragms, loaded on the convex side. The effective values of F for other materials can be so chosen that the points fall on the curve. This durve defines the stiffness of the diaphragms P/X over the given range of deflections as a function of D, effective thickness t, and the plate modulus of the material F. As long as the pressure-deflection curve is linear, the average stiffness P/X is the same as the local, or instantaneous, stiffness $\Delta P/\Delta X$. Beyond the range of linearity, it is necessary to specify what definition of stiffness is used in making comparisons. For example, at points A and B in figure 5, the stiffness is the same by either definition; at point C the average stiffness OP/PC is much less than the local stiffness $\Delta P/\Delta X$.

Because the diaphragms had been found to behave similarly when deflected similarly, that is, to the same X/D ratio within the limited range, it was considered probable that the similarity would hold for larger deflections. In order to reduce the observations to a form adapted to test this assumption, the following procedure was adopted:

The pressure-deflection data were plotted for a number of diaphragms of different materials, sizes, and thicknesses. From the average stiffnesses of the diaphragms up to $\frac{X}{D} = 0.02$, values of F were determined that would make the representative points for the diaphragms fall on the curve of figure 6.

The various determinations of F for diaphragms of the same material were averaged to obtain the values listed in table III.

Because the curve of figure 6 relates to reinforced diaphragms loaded on the convex side, the values of the modulus for other conditions derived from this curve are only relative. The values of F derived for diaphragms supposedly alike sometimes vary by as much as 1,000,000 pounds per square inch. Predictions based on the average values listed will therefore probably not be much more exact.

The plate modulus of reinforced beryllium copper previously reported (reference 9) differs slightly from the average given in table III. Although the average includes measurements made on diaphragms of slightly different chemical composition, no significant correlation with composition is apparent. The computed modulus appears not to vary with diameter. Nominally identical diaphragms sometimes differ in modulus by as much as 1,000,000 pounds per square inch, which is also the average deviation from the mean for all the reinforced diaphragms of this material. The modulus for unreinforced beryllium-copper diaphragms had a deviation from the mean of 700,000 pounds per square inch.

A few measurements on the other materials indicated less deviation from the mean. There was no significant difference of modulus between diaphragms formed of soft and quarter-hard material. This may be due in part to the fact that the soft materials were drawn in many cases to their maximum allowable reduction, whereas the technique followed for the quarter-hard materials probably resulted in diaphragms only slightly harder than those formed of the soft material.

In order to determine the value of t to use for each diaphragm, the thickness at the top of each corrugation was determined at eight points, by a micrometer with ball points. Readings were made to 0.0001 inch. The thicknesses of the several corrugations were weighted in proportion to the relative contributions made by each corrugation to the deflection (reference 9). For diaphragms formed by the two-stage method, the weighted mean differed only slightly from the average thickness.

Shape of pressure-deflection curves.- In the application of diaphragms to particular purposes the shape of the pressure-deflection curves is of considerable importance. A detailed study of some of the factors that influence the shape of the pressure-deflection curves is therefore desirable.

In figure 5 some pressure-deflection curves for reinforced beryllium-copper diaphragms are shown, from which some indication of the general shape of the pressure-deflection curves can be obtained. Deviations from linearity can be graphically determined from these curves but other methods of presentation are more satisfactory.

One convenient method of presenting the pressure-deflection data in graphical form is to plot curves of deviation from linearity against either pressure of deflection. Because the similarity relations sought are expected to be related to deflection ratios rather than to actual deflection or to actual pressures, the deviations from linearity were expressed as percentages of the deflection $X = 0.04D$ and were plotted against values of X, expressed as a percentage of the diaphragm diameter D. Details of the computation follow: For the X/D value of 4 percent the average flexibility X/P was determined. Multiplying the pressures at selected deflections by the average flexibility gave the deflections that would correspond to a linear pressure-deflection relation. The percentage deviation from linearity was obtained by dividing the difference between the observed and calculated deflections by 0.04D.

Three curves showing the deviation from linearity for diaphragm of reinforced beryllium copper are presented in figure 7. Diaphragms of other materials follow more or less closely the curves for beryllium copper for the same values of t/D. Curve I is typical of diaphragms of low t/D ratios. Diaphragms of thinner materials or larger diameters, abnormally low t/D ratios, deviate more widely from linearity and may deform suddenly at from 3 to 5 percent D. Diaphragms of the shape used for which the t/D ratio is approximately 2×10^{-3} have characteristically small deviations from linearity. Curve II shows deviations of less than 1 percent (of 4 percent D) in the range of deflections up to 4.6 percent D. The deviation from linearity when t/D is greater than 2×10^{-3} is shown by curve III. For larger values of t/D the effect is still more pronounced.

The average flexibilities of a number of diaphragms have been computed. A few typical curves of average flexibilities divided by the flexibility at $X = 2$ percent D plotted against deflection as a percentage of D are shown in figure 8. Also in figure 9 the variation of the ratios of the average flexibilities at $X = 0.04D$ to that at $X = 0.02D$ are shown. These data indicate that this ratio of flexibilities varies linearly with the t/D ratio.

These curves as well as those in figure 7 show that, for diaphragms of the shape studied, the nearest approach to pressure-deflection linearity for moderate deflections (up to $X = 0.04D$) is obtained with a ratio of $t/D = 2 \times 10^{-3}$. For t/D larger or smaller, the deviation from linearity becomes quite marked for deflections greater than 0.02D. Diaphragms with $t/D < 1 \times 10^{-3}$ may have local flexibilities over a short part of their range approximately ten times the flexibility at $X = 0.02D$. At slightly higher deflections ($X = 0.03D$ to 0.04D, depending on t/D), a sudden deformation of the diaphragm occurs, although no instability is apparent in the very flexible range before deformation. The curves shown are for reinforced beryllium-copper diaphragms.

Plots similar to the one shown in figure 9 for unreinforced diaphragms of all the materials tested indicated no significant variation among materials. For all values of $t/D > 1.6 \times 10^{-3}$ the points showed good agreement with the curve of figure 9 except that the corresponding points were shifted about 0.2×10^{-3} t/D to the left.

Unreinforced beryllium-copper diaphragms with t/D ratios below 1.6×10^{-3} were found to have partly slack centers and gave results that varied considerably from one diaphragm to another.

Effect of variation of corrugation depth.- It should be emphasized that the foregoing discussions apply to only one diaphragm shape. Some interesting incidental results were obtained from diaphragms fabricated for an airspeed indicator, on the effect of changing the depth of corrugation of 3-inch diaphragms. The depth of corrugation was varied by forming the diaphragm with one or more thicknesses of dental dam between the blank and the NBS No. 1 shape die. A number of diaphragms with approximately equal t/D ratios were formed from beryllium-copper blanks 0.005 inch thick with corrugation depths varying from the NBS No. 1 shape to less than half the usual depth. For these diaphragms t/D was approximately 1.6×10^{-3}. The diaphragm with normal corrugations had the usual flexibility curve for this t/D value. (The curve was approximately like curve III, fig. 8). A diaphragm with a 20 percent reduction in depth of corrugation had a flexibility curve more nearly like curve IV. A diaphragm with a corrugation depth of slightly less than half the normal depth of corrugation had a flexibility curve corresponding to a much higher t/D value. The deflection of this diaphragm showed a surprising linearity with equivalent airspeed (the deflection was proportional to the square root of the applied pressure). Over the range 150 to 500 miles per hour, the maximum deviation was about 3 miles per hour, when the pressure was applied to the convex side. When the pressure was applied to the concave side, the deviation from airspeed linearity was about 8 miles per hour.

This example indicates the very important effect of the corrugation depth on the pressure-deflection characteristics of a diaphragm and the desirability of investigating the performance of other shapes.

Hysteresis

Some observed hysteresis curves are shown in figures 10 and 11. The curves in figure 10 are for four different diaphragms. The curves in figure 11 are for the same beryllium-copper diaphragm (curve III, fig. 10) for different maximum deflections. The aftereffect, that is, the hysteresis at zero pressure, was so small in these experiments that the hysteresis curve for all practical purposes terminates at zero on the ordinate scale.

In curve III of figure 10 is indicated a double maximum, which appears again in figure 11. In general, the hysteresis data show less scatter for smaller total deflections where the water column was used and the uncertainty in pressure measurement was therefore smaller. The scatter shown is no larger than the errors in determination of pressure. The curves in figures 10 and 11 are typical of all the materials tested for pressure applied to either the convex or the concave side of the diaphragm. While the scatter of points is rather large in some instances, repeat tests indicate that the several maximums shown may be real. However, further investigation with more sensitive apparatus is required before any conclusions are justified.

Of special interest is the variation of the maximum hysteresis with maximum deflection. The curves in figure 12 show the maximum percentage hysteresis plotted against the maximum deflection expressed as percentage of D. The hump in the first part of the curve is significant. It would appear to indicate that, for the smallest percentage hysteresis, a diaphragm should be chosen which, under the conditions of use, will be deflected to several percent of its diameter. The hump exists in similar curves for diaphragms of each of the materials studied and is therefore believed to be a rather general phenomenon.

It would be highly desirable to determine whether an analogous hump occurs in the percentage-hysteresis curve for diaphragms normally loaded, that is, for cycles of variation of loading with respect to a fixed load (not zero, as in the present study). This knowledge would be of great value in analyzing the performance of altimeters, for instance, in which an evacuated capsule is normally under its maximum load. Although no quantitative explanation of the cause of these humps is available, it has been suggested that they may be due to local snap action. Whatever the ultimate explanation of the hysteresis effects may be, the immediate end will be served by empirical comparisons. The curves in figure 12 show that the curves for $1\frac{1}{2}$-inch diaphragms differ somewhat from the others in having wider humps.

In the upper chart of figure 13 the maximum percentage hysteresis for various maximum deflections from 1 to 4 percent D is plotted against the diameter of the diaphragms. The height of the hump in the maximum percentage-hysteresis curve varies somewhat with the diaphragm diameter. This variation is shown in figure 13 by the curve marked "Maximum hysteresis." The deflections followed by the greatest maximum percentage hysteresis are shown in the lower chart of figure 13 for various diameters.

The curves in figure 13 were plotted from averages for a number of diaphragms of unreinforced beryllium copper. Diaphragms of other materials agree quite closely, provided that the percentage D for which the average is taken is well within the pressure limits. There appears to be a definite but nonlinear variation of maximum percentage hysteresis with diaphragm diameter. For deflections up to 4 percent D the percentage maximum hysteresis for $1\frac{1}{2}$-inch diaphragms is approximately double the percentage for $2\frac{1}{2}$-inch diaphragms. The maximum hysteresis tends to approach a constant value as the diameter and the maximum deflection increase.

If a diaphragm of the shape investigated is to be used in an instrument, a diaphragm of diameter greater than $1\frac{1}{2}$ inch should be used to keep hysteresis effects to a minimum. For example, with deflections of 2 percent D the maximum hysteresis is usually about 0.8 percent for a $1\frac{1}{2}$-inch diaphragm as compared with 0.3 percent for a 3-inch diaphragm.

For deflections up to about 3 percent D there are no significant differences in hysteresis among beryllium copper, phosphor bronze, and K-Monel. As phosphor bronze approaches its deflection limit, around 4 to 5 percent D, there is a sharp increase in maximum percentage hysteresis. The minimum value of the maximum percentage hysteresis for beryllium copper is in the 6 to 7 percent D region. The minimum is usually about 0.2 percent and may be as small as 0.1 percent. For phosphor bronze the minimum is usually about 0.3 to 0.4 percent. K-Monel has a minimum hysteresis at 4 to 5 percent D of about 0.3 percent.

It is desirable that a diaphragm be used whenever possible in the range where hysteresis effects are a minimum, that is, about X = 3 to 7 percent D. As previously discussed, larger diameters should also be used if the hysteresis effects are an important consideration.

In general, the maximum-hysteresis curves show an increase in the region of the load limit. This increase is fairly sharp for phosphor bronze and the nickel alloys. For beryllium copper the increase in hysteresis is not so pronounced. This increase in the maximum hysteresis is an indication of maximum working range. A table of suggested maximum deflection limits for the various diaphragms tested, based on these and other considerations, is given in table IV.

Drift, Aftereffect, Recovery, and Zero Shift

Measurements of drift and recovery for loads suddenly applied or released show considerable variation from one diaphragm to another. This variation may be due in part to the fact that it is impossible, with the liquid manometers, to measure and maintain the pressure to the high sensitivity of the micrometer (5×10^{-6} in.). When a given load is applied to the diaphragm, the pressure must be gradually increased to its final value over a period as long as 2 to 6 seconds to prevent an overpressure surge. If measurements are to be taken immediately after application of the load the effect of the time between the application of the load and the first reading must be considered. However, some very definite indications of the magnitude of the drift, observed largely on beryllium copper, may be pointed out.

Within 10 seconds after the application of pressure the deflection was within about 1 percent of the final deflection, for a final deflection of 5 percent D. At the end of the first minute the difference had fallen to less than 0.2 percent. After about 20 minutes the drift became so small that it could not be detected in the succeeding hour. The time of drift decreases for smaller deflections and increases considerably for larger deflections.

The recovery curve is not, as might be expected, a reversal of the drift curve. The deflection decreases rapidly to a minimum in about 20 to 30 seconds after the release of the pressure. This minimum is usually about the same as the final recovery point or in some cases is slightly negative. The deflection then increases to a maximum (0.2 to 0.3 percent of the maximum deflection for a maximum deflection of 5 percent D) in about 50 to 60 seconds, and thereafter falls off more or less rapidly, depending on the magnitude of the previous pressure load, to its final value. The time for complete recovery varies considerably for different diaphragms. After a deflection of 5 percent D the recovery time may be as short as 5 minutes for some diaphragms and as long as 1 hour for others. The average recovery takes two to three times as long as the previous drift under load.

For stepwise loading the drift after 1 to 3 minutes at each step (10 to 20 steps in the loading cycle) was too small to be detected for deflections up to 5 percent D. Even for deflections up to 7 percent D the readings were essentially constant after 3 to 6 minutes. For stepwise reduction in loading constancy of deflection was attained in approximately the same time. Complete recovery at zero load took place within as little as 1 or 2 minutes following loadings up to 5 percent D with stepwise unloading. For higher loading the recovery time rapidly increased. For deflections of 7 percent D or more the recovery of some diaphragms required some hours, although other diaphragms recovered within a few minutes.

The average residual deflection at zero load (aftereffect) for beryllium-copper diaphragms 1 minute after a slow unloading from 5 percent D is only 0.02 percent of the total deflection. At 7 percent D the aftereffect is 0.04 percent 1 minute after the load was removed. Other materials show a sharper increase in aftereffect at higher deflections. This point of sharp increase of both aftereffect and time of recovery roughly corresponds to the point at which an excessively large number of loadings are required to stabilize the diaphragm (that is, to eliminate the zero shift) and may therefore be taken as a fair indication of the useful limit of deflection.

A beryllium-copper diaphragm would probably require several hundred loadings at about 8.5 percent D to stabilize the zero for loadings up to 8 percent D. Ten loadings at about 6.5 percent D will usually stabilize the zero for loadings up to 6 percent D, and one or two loadings at 5.5 percent D will stabilize a diaphragm for loadings up to 5 percent D. Diaphragms of other materials tested have lower deflection limits and require relatively larger numbers of loadings to attain stability. Within the deflection limits listed in table IV, the zero shift for a stabilized diaphragm during normal use was no greater than the sensitivity of the micrometer (5×10^{-6} in.). For a 2-inch diaphragm of beryllium copper this shift corresponds to less than 0.005 percent of the total deflections.

Based on these considerations of deflection and on considerations of hysteresis previously discussed, the suggested limits of maximum deflection for diaphragms of the various materials formed to the shape investigated and heat-treated as described are given in table IV. The tabulated list is subject to certain restrictions listed in the discussion that follows.

There is no apparent dependence of the percent D deflection limit for beryllium copper on either thickness or diameter when t/D exceeds 1.6×10^{-3}. Below this value of t/D the maximum deflection is strictly limited by a snap deformation of one of the outer corrugations. The diaphragms perform satisfactorily up to their snap deformation point. Where t/D is between 1.0×10^{-3} and 0.7×10^{-3} the snap deformation point is in the range 3 to 4 percent D. For $t/D = 1.6 \times 10^{-3}$ the diaphragm deforms above the load limit as set by zero shift, slightly above 8 percent D.

No measurements were made on thin diaphragms of other materials, but they would presumably show a like snap deformation. For many diaphragms this deformation point would be above the deflection limits set by other considerations.

The suggested deflection limit for beryllium copper is listed as 5 to 7 percent D. It should not be assumed that variations between diaphragms indicate this variation of deflection limit but that the values of deflection limit chosen on the basis of different considerations usually fall within these limits. A deflection of 5 percent D represents the deflection from which recovery after removal of load is very rapid. A deflection of 7 percent D or higher represents the point above which excessive elastic defects become apparent.

A rough theoretical prediction of the comparative merits of the various materials in withstanding deflections may be obtained from the Knoop indendation number and the elastic modulus.

Because the hardness is an indication of the strength of the material and because, for a given strain or given deflection in diaphragms of the same diameter, the stress will be proportional to the elastic modulus, the deflection limit of stressed diaphragms would be expected to increase with the ratio of the hardness numbers to the elastic modulus. The numerical values of this ratio, based on the relative plate moduli (table III) for unreinforced diaphragms of the various materials, are listed in order in table IV for comparison with the ordering on the basis of suggested deflection limits derived from the previous considerations. The Knoop indentation numbers (table II) used were obtained for diaphragms that had been stress-relieved by heat treatment after forming. The sequence of the materials on this basis agrees quite well with that based on the experimental results, with the possible exception of Inconel, which may possibly not have been properly heat-treated for stress relief.

A knowledge of the hardnesses of stress-relieved materials may thus permit a reasonable prediction of the relative merits of many other possible diaphragm materials and, by interpolation between the experimental values for the materials studied, may even allow a quantitative estimate of performance.

Design and Selection of Diaphragms

From the design charts and formulas given in reference 9, together with the data reported here that extend the range of deflections considered, it is possible to predict for a given diaphragm of the particular shape studied, the shape of the pressure-deflection curve, the stiffness or flexibility, the useful load or deflection limit, and the magnitude of the hysteresis.

The following procedure may be used to select diaphragms for a given application: A load-deflection curve of suitable shape for the particular purpose is selected from figures 7 and 8. This curve determines a value of t/D; the corresponding value of FX/PD is obtained from figure 6. The diameter D is then computed from this value of FX/PD by substituting the desired sensitivity X/P and the plate modulus F of the material selected. With the value of D, the value of t can be determined. In practice, considerations of the available space may limit the diameter D. The deflection X must be within the deflection limits but should be as large as possible to keep hysteresis effects down to a minimum. The design may often be complicated by too many restrictions on the variables. Compromise must therefore be made among some of the desired features.

A numerical example may be helpful. Let us assume that a pressure-deflection curve shape with a high degree of linearity is desired for use in a suction gage. Figure 7 indicates that a high degree of linearity requires t/D to be approximately 2×10^{-3}. For this t/D ratio, $\frac{FX}{PD} = 7.8 \times 10^4$ from figure 6. Assume that the desired sensitivity is $\frac{X}{P} = \frac{0.01 \text{ in.}}{\text{lb/sq in.}}$ and that beryllium copper with a center reinforcement is to be used so that $F = 19.4 \times 10^6$ pounds per square inch for loading on the convex side.

Then

$$7.8 \times 10^4 D = 19.4 \times 10^6 \times 10^{-2}$$

or

$$D = \frac{19.4}{7.8} = 2.5 \text{ inches}$$

The required thickness is $t = 2 \times 10^{-3} \times 2.5 = 0.005$ inch.

This diaphragm will have a nearly linear pressure-deflection curve within about 1 to 2 percent (see fig. 7) to a deflection of 5 percent D or 0.125 inch, or 0.25 inch for a capsule of two diaphragms, which for the chosen sensitivity would correspond to a pressure of $12\frac{1}{2}$ pounds per square inch. Such a diaphragm, if properly seasoned, can be deflected to at least 7 percent D without damage. At 7 percent D the average flexibility will be about 85 percent of the average flexibility at 2 percent D. (See fig. 8.) The pressure required to deflect the single diaphragm to this limit would be $7 \times 2.5/0.85 = 20$ pounds per square inch. This diaphragm could then be used in a suction gage under full vacuum without injury.

For diaphragms formed by the two-stage method as described in this report, the thickness of sheet stock should be 10 percent greater than the desired diaphragm thickness. For single-stage formation the reduction in thickness may be 15 to 20 percent when the edges are firmly clamped; if the edges are allowed to draw, the reduction in thickness may be much less.

If K-Monel had been chosen instead of the beryllium copper used in the preceding example, the required diameter would have been 3.14 inches for the required sensitivity if the center were not reinforced and even larger if the center were reinforced. In such a case it would usually be desirable to reduce the sensitivity requirement or, as is customary, to use diaphragm capsules in order to reduce the diameter to reasonable limits.

Although the data and the curves presented in this report are mainly for diaphragms loaded on the convex side, the design formulas may also be used with a fair degree of approximation, for deflection in the other direction by using appropriate values of the modulus, proportional to those given in table III for beryllium copper.

National Bureau of Standards,
Washington, D. C., September 1942.

REFERENCES

1. Griffith, A. A.: The Theory of Pressure Capsules. R. & M. No. 1136, British A.R.C., 1928.

2. Smith, Stanley: On the Depression of the Centre of a Thin Circular Disc of Steel under Normal Pressure. Trans. Roy. Soc. Canada, third ser., vol. XVI, sec. III, May 1922, pp. 217-225.

3. Nadai, A.: Elastische Platten. Julius Springer (Berlin), 1925.

4. Federhofer, Karl: Über die Berechnung der dünnen Kreisplatte mit Grosser Ausbiegung. Eisenbau, vol. 9, 1918, pp. 152-166.

5. Way, Stewart: Bending of Circular Plates with Large Deflection. A.S.M.E. Trans., APM-56-12, vol. 56, no. 8, Aug. 1934, pp. 627-636.

6. Federhofer, K.: Zur Berechnung der dünnen Kreisplatte mit grosser Ausbiegung. Forschung auf dem Gebiete des Ingenieurwesens, Ausg. B, Bd. 7, Heft 3, May-June 1936, pp. 148-151.

7. Barta, J.: Über die Randwertaufgabe der Gleichmässig belasteten Kreisplatte. Z.f.a.M.M., Bd. 16, Heft 5, Oct. 1936, pp. 311-314.

8. Charron, Fernand: Etude des Capsules Aneroides. Sci. et Tech. du Ministere de L'Air, Pub. No. 160, (Paris), 1940.

9. Wildhack, W. A., and Goerke, V. H.: Corrugated Metal Diaphragms for Aircraft Pressure-Measuring Instruments. T.N. No. 738, NACA, 1939.

10. Knoop, Frederick, Peters, Chauncy G., and Emerson, Walter B.: A Sensitive Pyramidal-Diamond Tool for Indentation Measurements. Res. Paper 1220, Nat. Bur. of Standards Jour. Res., vol. 23, no. 1, July 1939, pp. 39-61.

11. Harrington, R. H., and Thompson, R. G.: The Precipitation Reaction in Cold Rolled Phosphor Bronze. Its Effects on Hardness, Conductivity, and Tensile Properties. Trans. Am. Soc. Metals, vol. 28, no. 4, Dec. 1940, pp. 933-948.

12. Beryllium Corporation of Pennsylvania, Engineering Data Sheets on Beryllium Copper Alloys, Berylco #25.

13. Staff Development and Research Division of the International Nickel Co.: The Heat Treatment of K-Monel and Z-Nickel. Heat Treating and Forging, vol 25, Dec. 1939, pp. 593-597.

14. Buckingham, E.: Model Experiments and the Forms of Empirical Equations. A.S.M.E. Trans., vol. 37, 1915, pp. 263-288.

TABLE I

CHEMICAL ANALYSES OF MATERIALS USED

Material / Element	Phosphor bronze	Beryllium copper	A-Nickel (nominal)	B-Monel (nominal)	K-Monel (nominal)	Inconel (nominal)
	Chemical composition (percent)					
Cu	95	97.3	0.04	32.2	30.3	0.14
Ni	---------	.26	98.99	65.01	64.81	78.96
Cr	---------	----------	---------	--------	--------	13.46
P	.18-.29	----------	---------	--------	--------	------
Be	---------	2.0-2.3	---------	--------	--------	------
Co	---------	< .01	.58	.41	.41	.53
Fe	.01	.03-.13	.13	1.07	.33	6.30
Sn	4.6	----------	---------	--------	--------	------
Pb	---------	< .01	---------	--------	--------	------
Mn	---------	< .01	.21	1.03	.34	.21
Si	---------	0-.02	.02	.04	.26	.17
C	---------	---------	.02	.02	.22	.21
S	---------	---------	.005	--------	.005	.015
Al	---------	0-.06	---------	--------	2.75	------
Zn	---------	0-.24	---------	--------	--------	------
Ti	---------	----------	---------	--------	.47	------
Mg	---------	----------	---------	.22	<.01	------
Cb	---------	----------	---------	--------	.10	------

TABLE II

HARDNESS OF DIAPHRAGM MATERIALS

Nominal thickness (in.)	Knoop indentation numbers (reference 10)			
	Sheet stock as received	Diaphragm blank or strip, heat treated	After formation	Formed and heat treated
Phosphor bronze				
0.002	152	150(100 hr, 250°C)	Could not be formed	---------------
.003	179	122(100 hr, 250°C)	Could not be formed	---------------
.004	198	105(1 hr, 425°C)	----------	---------------
		177(100 hr, 250°C)	----------	183(50 hr, 250°C)
.006	200	118(1 hr, 425°C)	----------	---------------
		180(100 hr, 250°C)	----------	---------------
.008	222	196(100 hr, 250°C)	211	192(50 hr, 250°C)
Beryllium copper				
0.002	----------	336(1 hr, 300°C)	----------	336(1 hr, 300°C)
.004	----------	351(1 hr, 300°C)	----------	345(1 hr, 300°C)
.005	----------	335(1 hr, 300°C)	----------	327(1 hr, 300°C)
.003	----------	317(1 hr, 300°C)	----------	324(1 hr, 300°C)
.008	125	317(1 hr, 300°C)	----------	334(1 hr, 300°C)
A-Nickel				
0.006	Soft, 80	----------------		170(1 hr, 330°C)
.006	Quarter-hard, 148	----------------	Could not be formed	---------------
B-Monel				
0.006	Soft, 102	----------------	----------	200(1 hr, 330°C)
.006	Quarter-hard, 222	----------------	Could not be formed	---------------
K-Monel				
0.006	Soft, 192	----------------	273	324(16 hr, 580°C)
.006	Quarter-hard, 215	----------------	----------	335(16 hr, 580°C)
Inconel				
0.006	Soft, 248	----------------	----------	332(1 hr, 425°C)
.006	Quarter-hard, 272	----------------	----------	344(1 hr, 425°C)

TABLE III

VALUES OF RELATIVE PLATE MODULUS F FOR DIAPHRAGM MATERIALS

Material	Pressure on convex side		Pressure on concave side	
	Not reinforced (lb/sq in.)	Reinforced (lb/sq in.)	Not reinforced (lb/sq in.)	Reinforced (lb/sq in.)
Phosphor bronze	15.1×10	----------	----------	----------
Beryllium copper	17.0	19.4×10^6	13.8×10^6	16.7×10^6
A-Nickel	[a]31.7	----------	----------	----------
B-Monel	22.2	----------	----------	----------
K-Monel	24.5	----------	----------	----------
Inconel	26.4	----------	----------	----------

[a]At 1.5 percent D.

TABLE IV

RELATIVE ORDER OF DIAPHRAGM MATERIALS ON THE BASIS OF DEFLECTION LIMITS AND RATIOS OF INDENTATION NUMBER TO MODULUS

Material	Suggested deflection limits for diaphragms (percent D)	Ratio of Knoop indentation number to relative modulus
Beryllium copper	5 to 7	197×10^{-5}
K-Monel	4 to 5	135
Phosphor bronze	4 to $4\frac{1}{3}$	127
Inconel	3 to $3\frac{1}{3}$	128
B-Monel	2	90
A-Nickel	$1\frac{1}{3}$	54

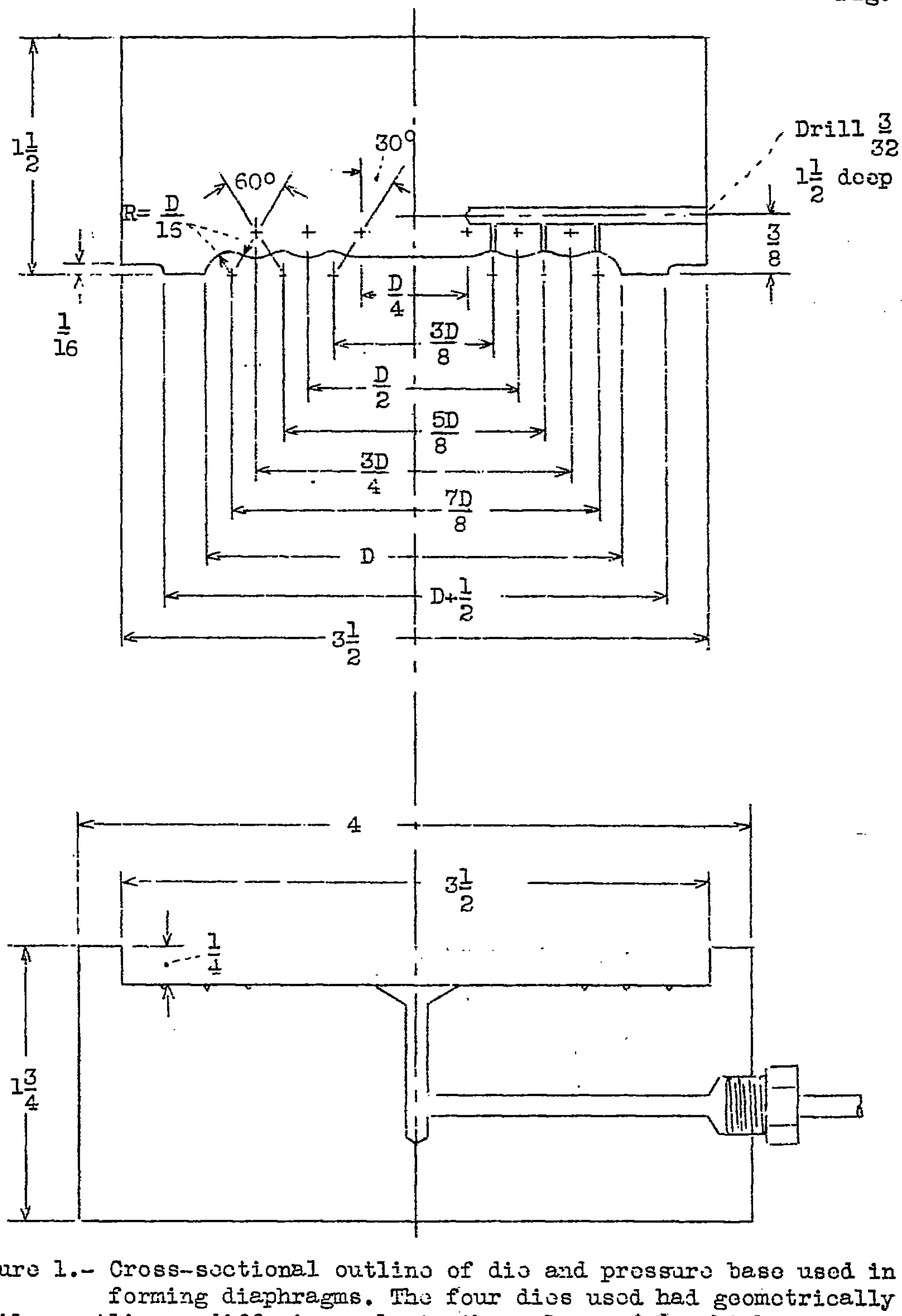


Figure 1.- Cross-sectional outline of die and pressure base used in forming diaphragms. The four dies used had geometrically similar outlines, differing only in the values of D, which were $1\frac{1}{2}$, 2, $2\frac{1}{2}$, and 3 inches.

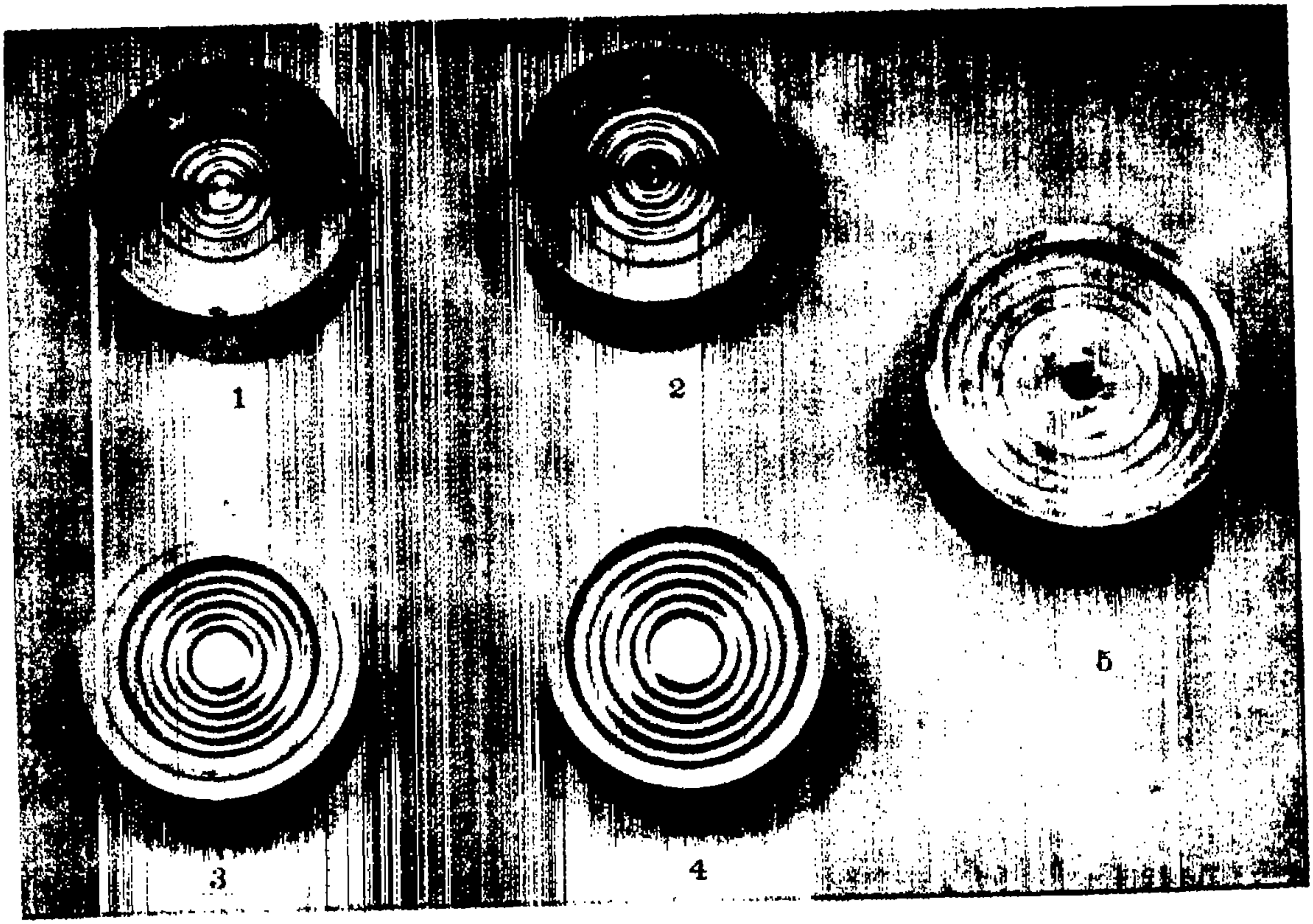
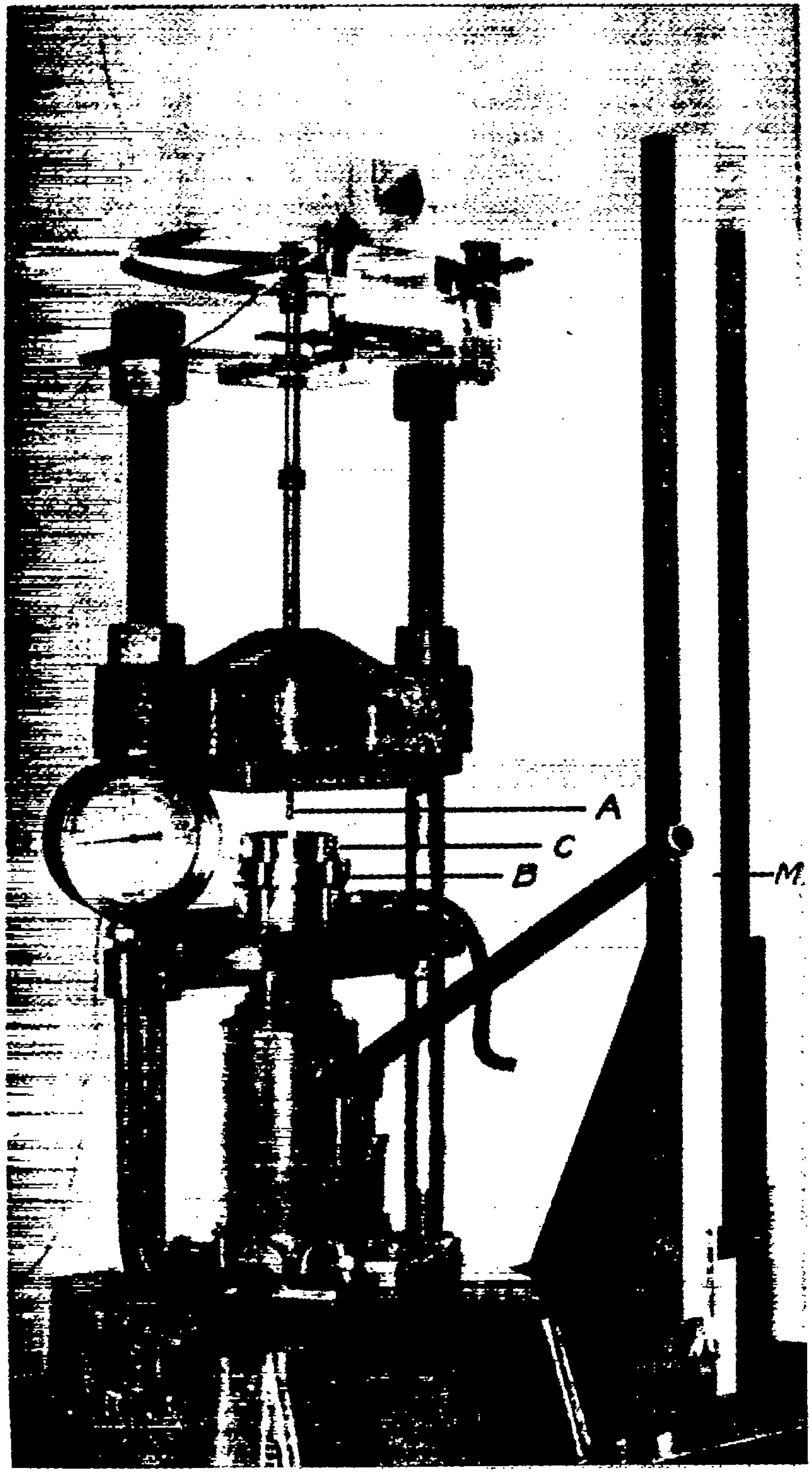


Figure 2.- Photograph of dies 1 to 4 and the base for the dies, 5.



The diaphragms were clamped in the pressure chamber B, by the cylinder C, when the lower platen was raised. The pressures were measured by the manometer M. The deflections were measured by the micrometer A, which was turned by the graduated wheel E.

Figure 3.- View of the press used in making and testing the diaphragms, with testing apparatus.

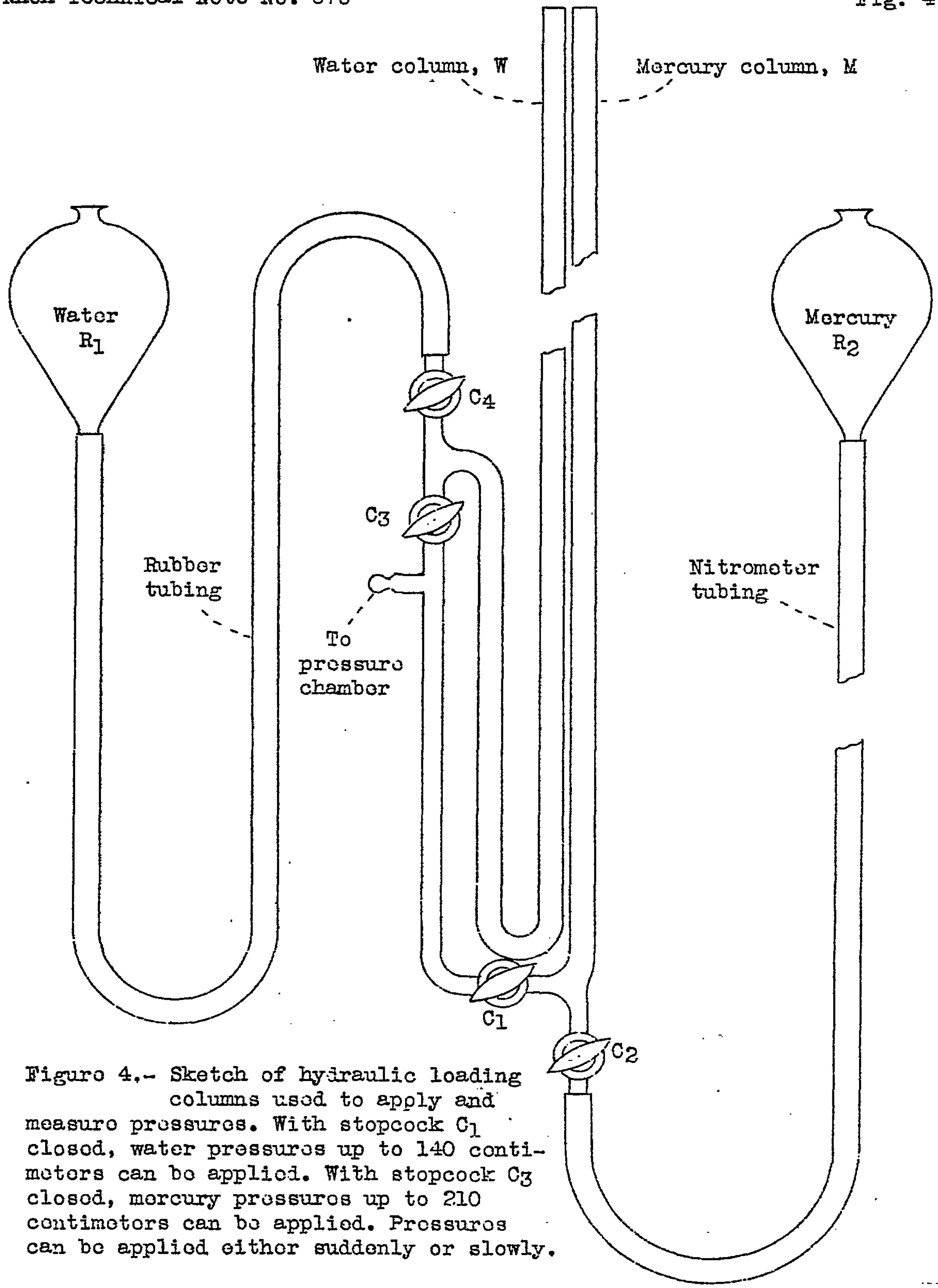


Figure 4.- Sketch of hydraulic loading columns used to apply and measure pressures. With stopcock C_1 closed, water pressures up to 140 centimeters can be applied. With stopcock C_3 closed, mercury pressures up to 210 centimeters can be applied. Pressures can be applied either suddenly or slowly.

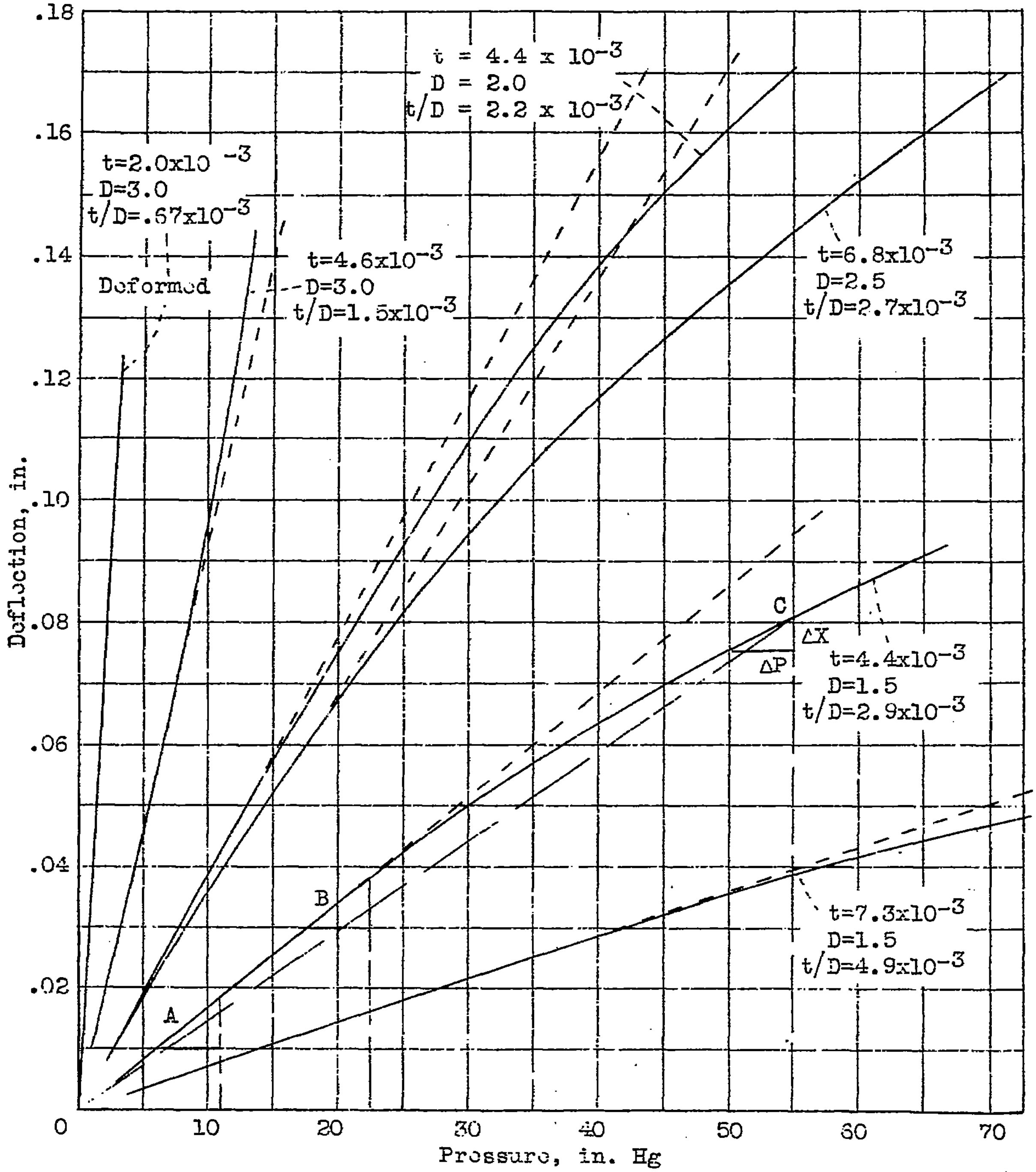


Figure 5.- Pressure-deflection curves for several reinforced beryllium-copper diaphragms. The dotted lines are extensions of the straight lines through the X = 0.02D points.

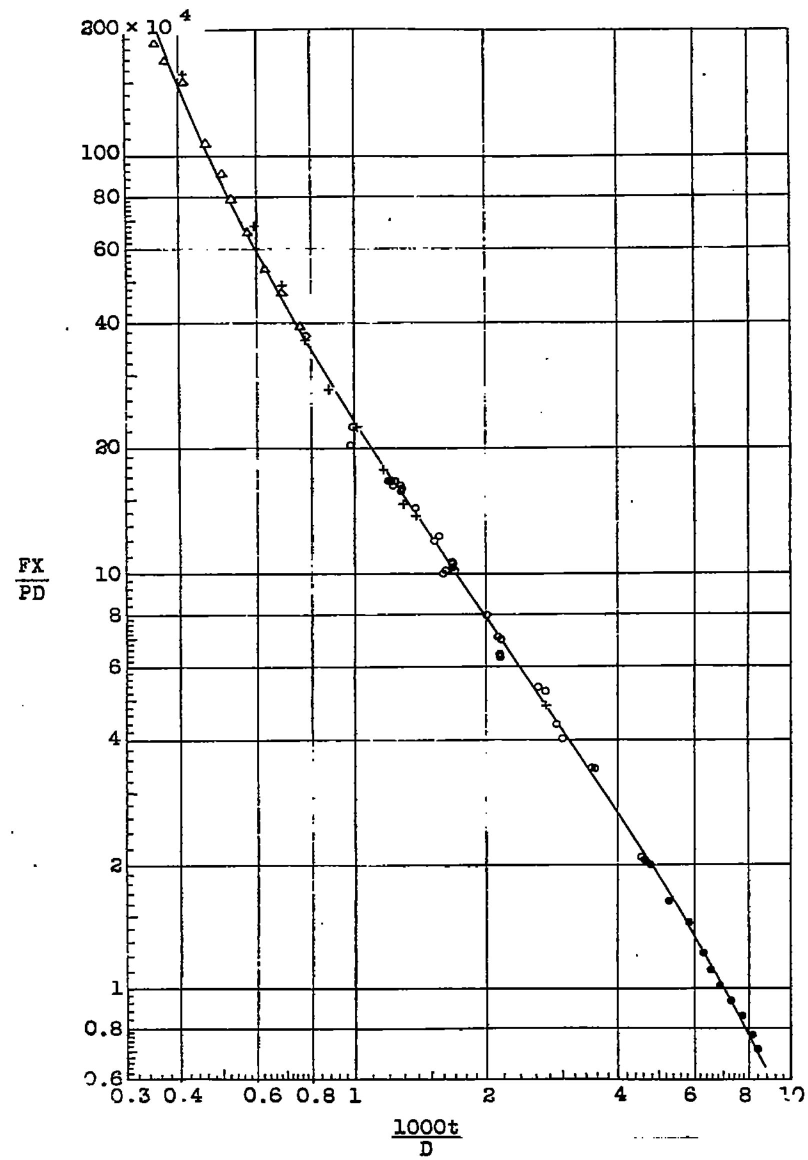


Figure 6.- The pressure-deflection data on beryllium-copper diaphragms plotted to show the relation between the dimensionless ratios FX/PD and t/D. The effective value of F (approximately $E/1 - \sigma^2$) was taken as 18.9×10^6 pounds per square inch. (10^9 mm Hg). The points marked with open circles represent different diaphragms. Those marked with crosses, triangles, or solid dots represent the series of measurements on three different diaphragms after successive etchings.

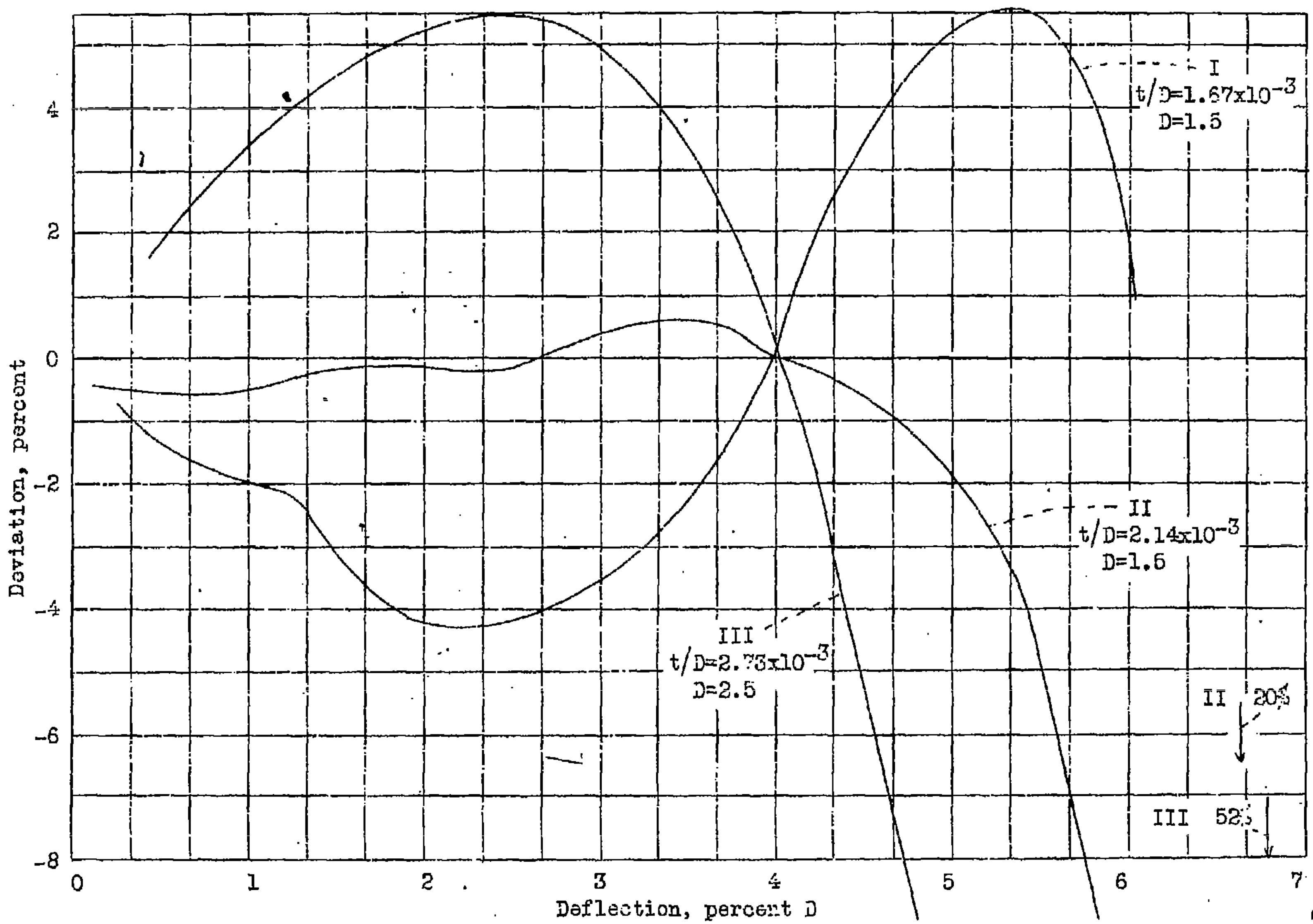


Figure 7.- The deviations from linearity of pressure-deflection curves for reinforced beryllium-copper diaphragms. The deviations from the straight line passing through the origin and the load-deflection curve at X = 0.04D are plotted as percentages of 0.04D.

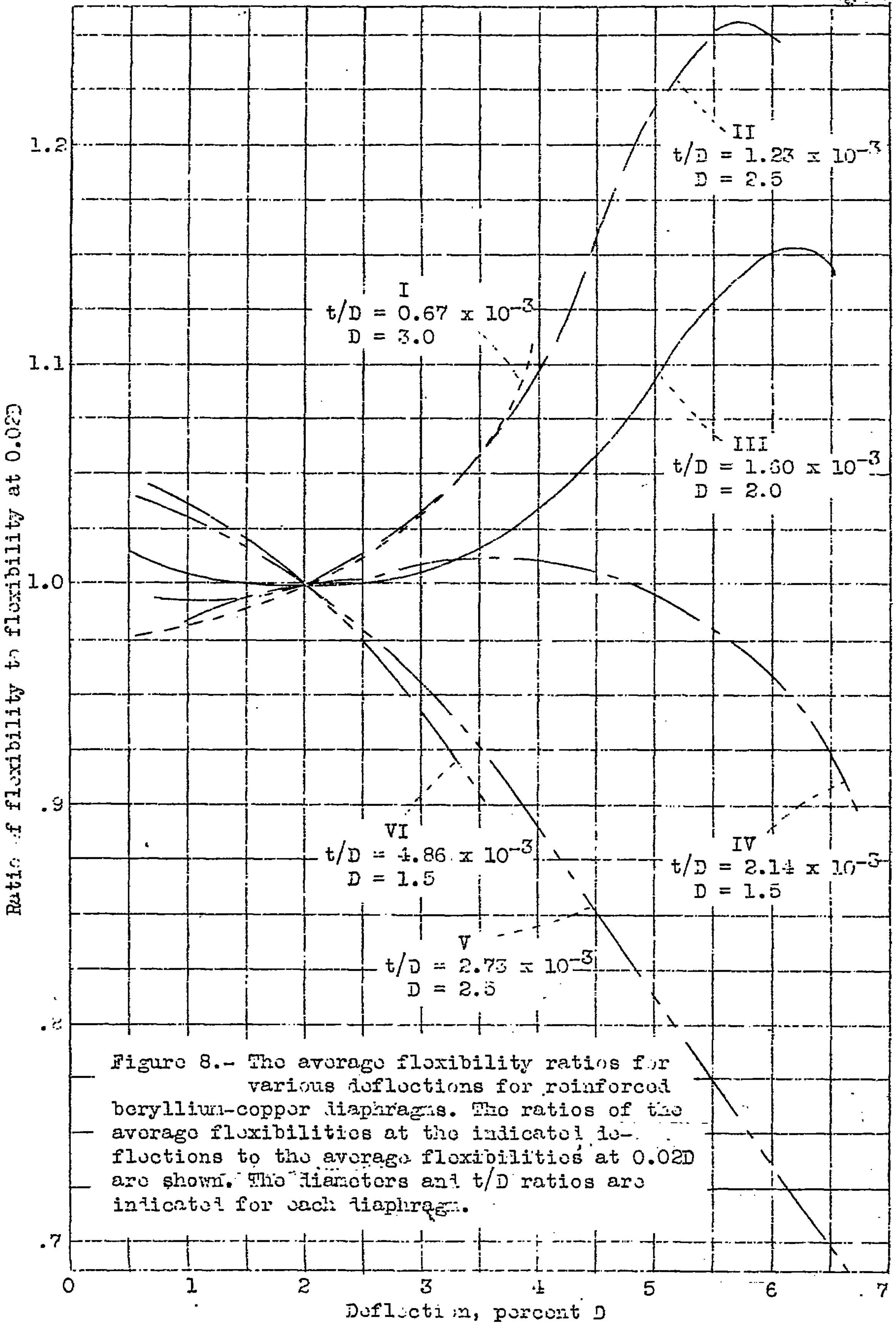


Figure 8.- The average flexibility ratios for various deflections for reinforced beryllium-copper diaphragms. The ratios of the average flexibilities at the indicated deflections to the average flexibilities at 0.02D are shown. The diameters and t/D ratios are indicated for each diaphragm.

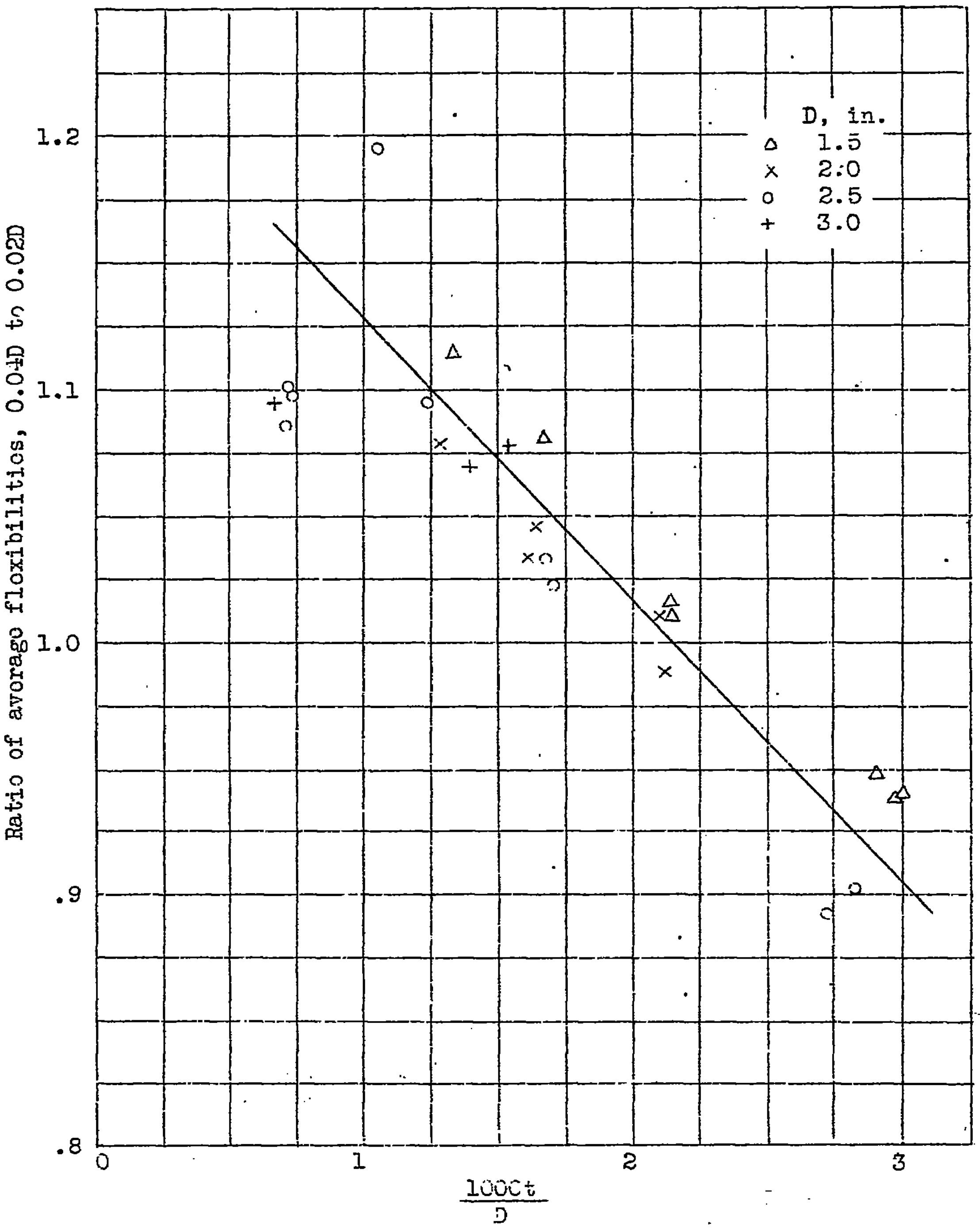


Figure 9.- The variation of the average flexibility with t/D for reinforced beryllium-copper diaphragms. The ratios of average flexibility at 0.04D to that at 0.02D are plotted against t/D.

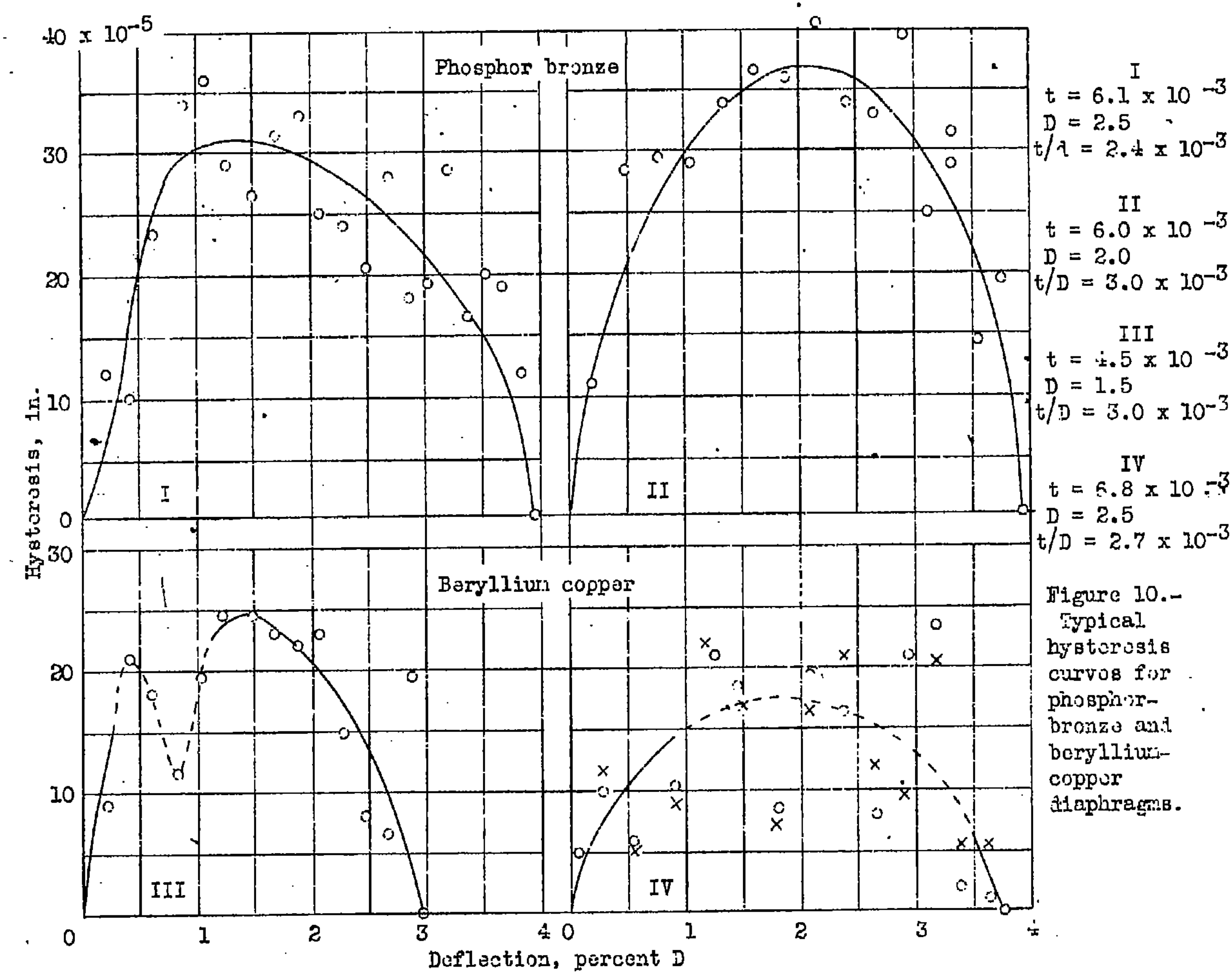


Figure 10.- Typical hysteresis curves for phosphor-bronze and beryllium-copper diaphragms.

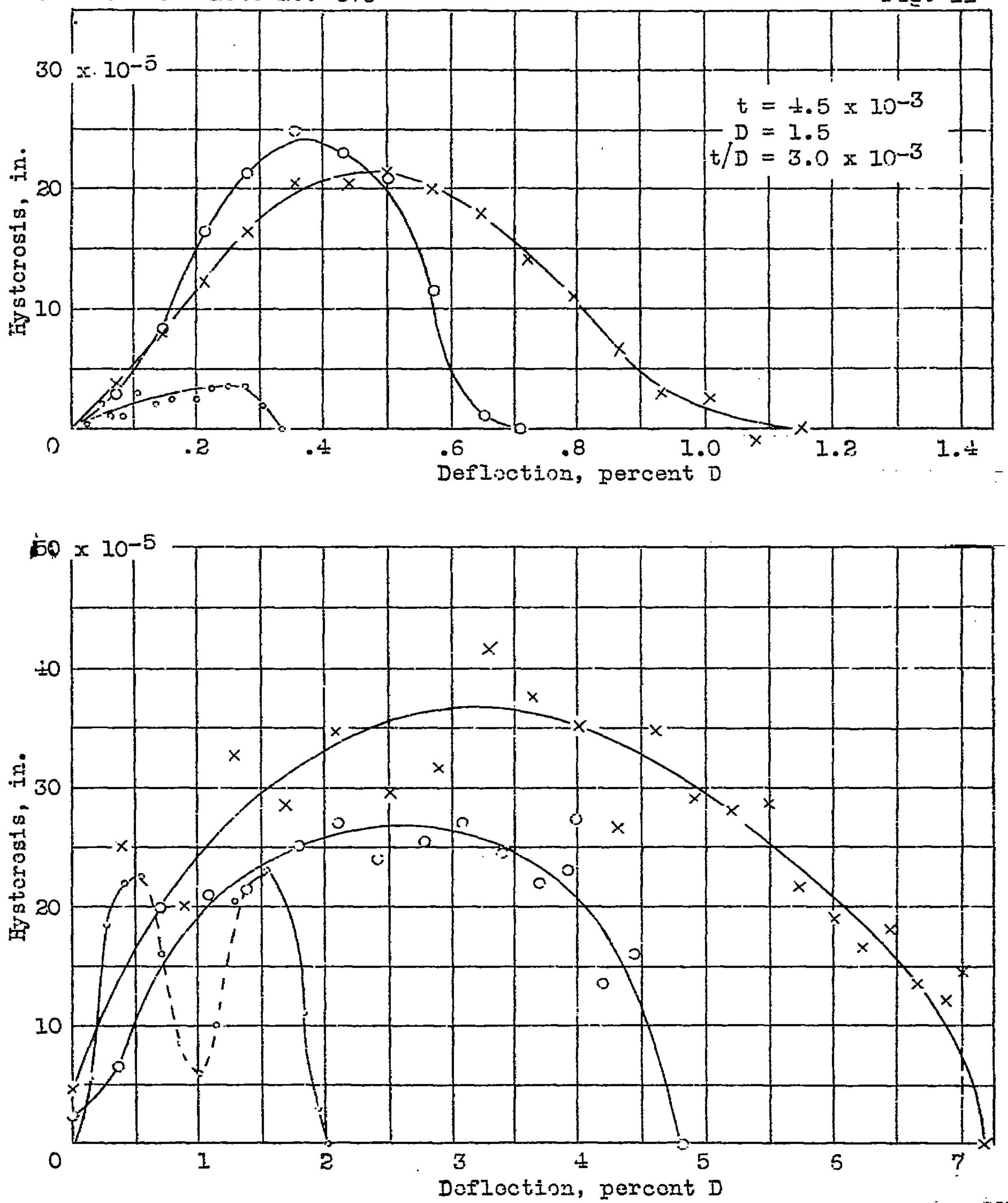


Figure 11.- Hysteresis curves for a beryllium-copper diaphragm for various maximum deflections. These curves are for the same diaphragm as that of curve III of figure 10.

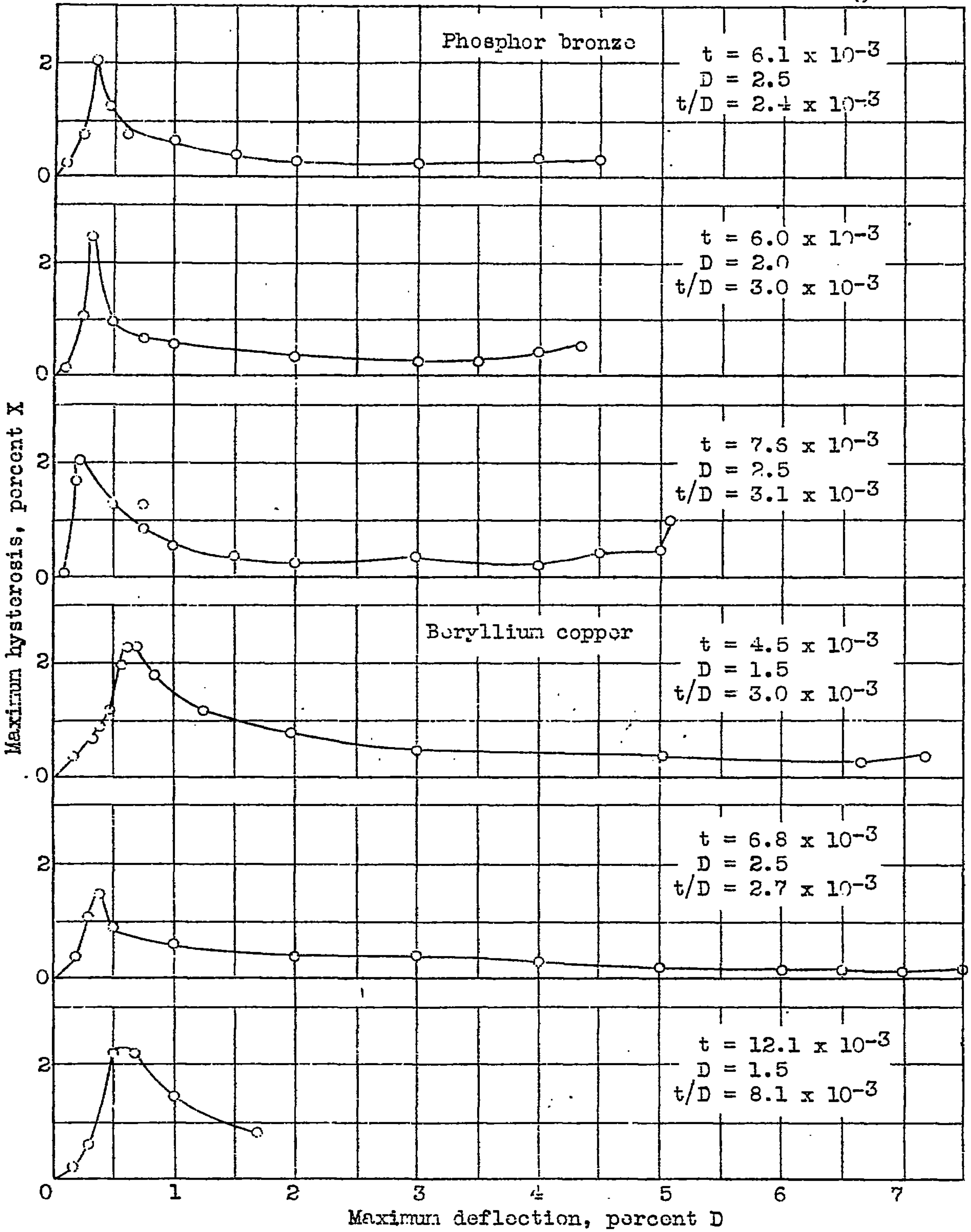


Figure 12.- The maximum percentage hysteresis obtained from curves in figures 10 and 11 and others plotted against the maximum deflections expressed as percentages of the diaphragm diameter.

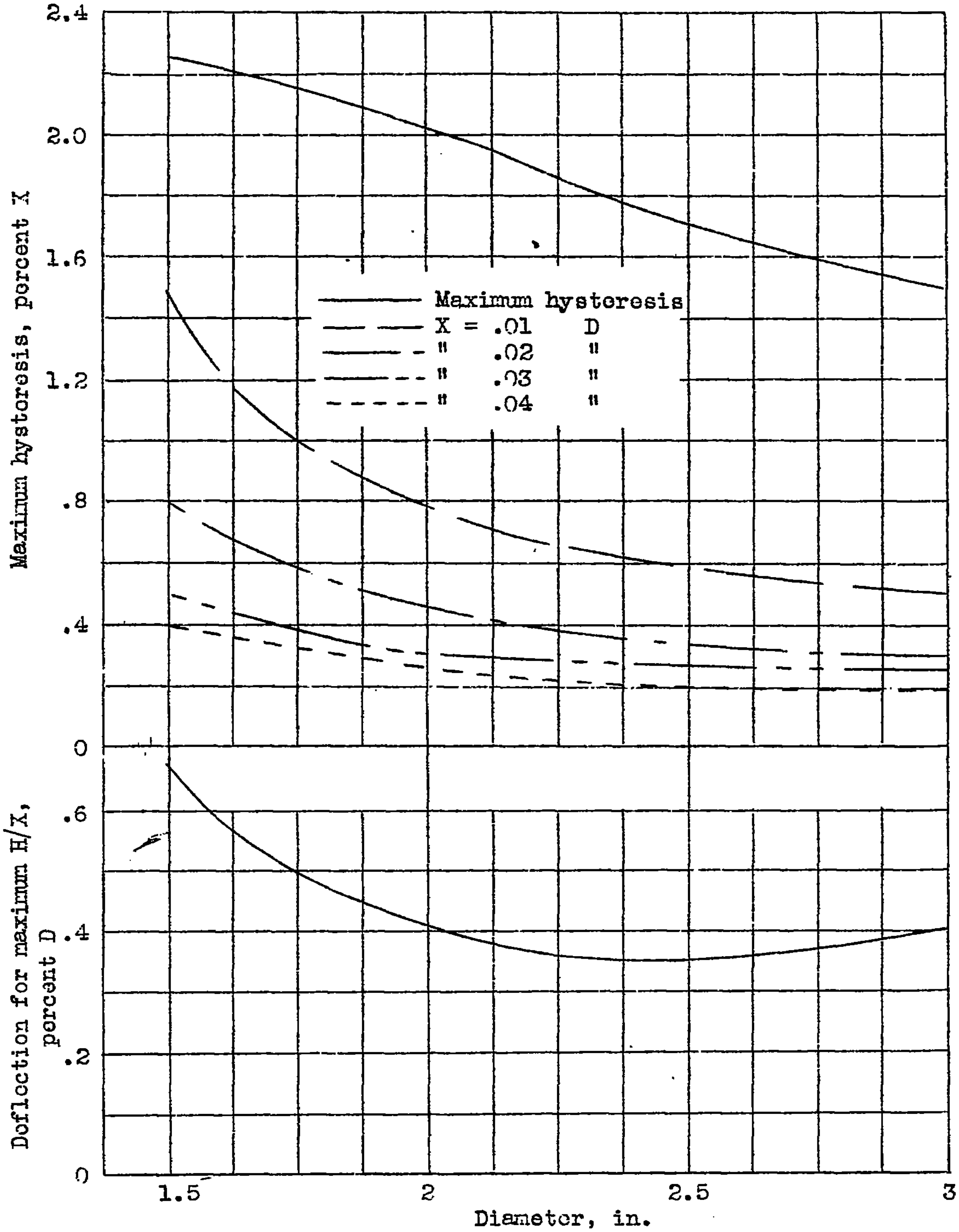


Figure 13.- The variation of the percentage maximum hysteresis for various deflections with the diaphragm diameter is shown in the upper group of curves. The curve marked maximum hysteresis is for deflections that are followed by the greatest percentage hysteresis. These deflections, as percentages of D, are shown in the lower chart for various diameters.